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User-based gesture vocabulary for form creation during a product design process

by

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‘This thesis is the result of the author’s original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.’

Signed: Date: 18 May 2021

Abstract

There are inconsistencies between the nature of the conceptual design and the functionalities of the computational systems supporting it, which disrupt the designers' process, focusing on technology rather than designers' needs. A need for elicitation of hand gestures appropriate for the requirements of the conceptual design, rather than those arbitrarily chosen or focusing on ease of implementation was identified.

The aim of this thesis is to identify natural and intuitive hand gestures for conceptual design, performed by designers (3^{rd}, 4^{th} year product design engineering students and recent graduates) working on their own, without instruction and without limitations imposed by the facilitating technology. This was done via a user centred study including 44 participants. 1785 gestures were collected. Gestures were explored as a sole mean for shape creation and manipulation in virtual 3D space. Gestures were identified, described in writing, sketched, coded based on the taxonomy used, categorised based on hand form and the path travelled and variants identified. Then they were statistically analysed to ascertain agreement rates between the participants, significance of the agreement and the likelihood of number of repetitions for each category occurring by chance. The most frequently used and statistically significant gestures formed the consensus set of vocabulary for conceptual design. The effect of the shape of the manipulated object on the gesture performed, and if the sequence of the gestures participants proposed was different from the established CAD solid modelling practices were also observed.

Vocabulary was evaluated by non-designer participants, and the outcomes have shown that the majority of gestures were appropriate and easy to perform. Evaluation was performed theoretically and in the VR environment. Participants selected their preferred gestures for each activity, and a variant of the vocabulary for conceptual design was created as an outcome, that aims to ensure that extensive training is not required, extending the ability to design beyond trained designers only.

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List of appended papers

This thesis is partially based on two published journal articles and one conference paper, described below. They are appropriately cited throughout the thesis.

Paper 1: Vuletic, T, Duffy, A, Hay, L, McTeague, C, Pidgeon, L & Grealy, M 2018, 'The challenges in computer supported conceptual engineering design', *Computers in Industry*, vol. 95, pp. 22-37. https://doi.org/10.1016/j.compind.2017.11.003

Paper 2: Vuletic, T, Duffy, A, Hay, L, McTeague, C, Campbell, G, Choo, PL & Grealy, M 2018, 'Natural and intuitive gesture interaction for 3D object manipulation in conceptual design' Paper presented at 15th International Design Conference, Dubrovnik, Croatia, 21/05/18 - 24/05/18, https://doi.org/10.21278/idc.2018.0321

Paper 3: Vuletic, T, Duffy, A, Hay, L, McTeague, C, Campbell, G & Grealy, M 2019, 'Systematic literature review of hand gestures used in human computer interaction interfaces', *International Journal of Human Computer Studies*, vol. 129, pp. 74-94. https://doi.org/10.1016/j.ijhcs.2019.03.011

Paper 4: Vuletic, T, Duffy, A, Hay, L, McTeague, C, Campbell, G & Grealy, M, 'A novel user-based gesture vocabulary for conceptual design', *International Journal of Human Computer Studies, Volume 150, June 2021*,https://doi.org/10.1016/j.ijhcs.2021.102609

The work reported in each paper was conducted by the author of this thesis as an individual PhD student. Co-authors provided a varying level of general and editorial guidance during the publication process. Specifically the co-authors provided editorial guidance in terms of:

- Ross Brisco: Formal analysis (third coder for the full study),
- Gerard Campbell: Study administration (communication with the study participants to arrange the study sessions),
- Pei Ling Choo: Writing – review,
- Alex Duffy: Conceptualization, resources, funding acquisition (Route to impact funding and study funding), supervision,

- Madeleine Grealy: Formal analysis (advice with regards to statistics), resources, funding acquisition (Route to impact funding and study funding), Supervision,
- Laura Hay: Conceptualization (inter coder reliability advice), writing - review & editing,
- Chris McTeague: Formal analysis (second coder for the full study),
- Laura Pidgeon: Writing – review.

VR application used in the evaluation of the gesture vocabulary “Natural gestures VR/AR CAD interaction system” (reported in Chapter 7) was developed at University of Strathclyde. Mr Ryan Welsh, a researcher at the department, was hired to programme the application based on the specification designer by the author of this thesis. Author of the thesis provided guidance and testing. The funding for the development was provided by CATAPULT Route to Impact funding awarded by the AFRC in 2018 - AFRC_CATP_1220_RTI.

Signed: Date: 18 May 2021

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Nomenclature

Abbreviation	**Meaning**
2D	Two-dimensional
3D	Three-dimensional
6DOF	6 Degrees of Freedom
AR	Augmented Reality
AgR	Agreement Rate
BCI	Brain Computer Interfaces
Ben	Bend
C/SPl	Create/Select Plane
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAED	Computer Aided Engineering Design
CAM	Computer Aided Manufacturing
Copy	Copy
CV	Cup variant
D	Deselect
Drw	Draw
EC	Extrude cut
ECS	Extrude cut shallower
ED	Extrude down
EEG	Electroencephalography
EExt	End the Extrude
EMG	Electromyography
EU	Extrude up
Ext	Extrude
ExtC	Extrude cut
F/In	Fill In
FBS	Function -Behaviour-Structure
Fil	Fillet
FMEA	Failure Mode and Effects Analysis
GUI	Graphical User Interface
HCI	Human Computer Interface
HMD	Head Mounted Display
HV	Hexagonal plate variant
ISO	International Organisation for Standardisation
Join	Join
Loft	Loft
MulPat	Multiply/Pattern
NURBS	Non-Uniform Rational B-Spline
PDE	Product Design Engineering
PV	Phone variant
RCCW	Rotate counter clockwise
RCW	Rotate clockwise
Res	Resize

Abbreviation	Meaning
RFID	Radio-frequency identification
Rot	Rotate
S	Select
Scl	Scale
Scul	Sculpt
SDK	Software development kit
Select	Select
Slice	Slice
Snap	Snap fingers to sketch
Sph	Sphere
Stick	Stick
TD	Translate down
TL	Translate left
TR	Translate right
Tra	Translate
TRIZ	Design innovation tool
TRL	Technology Readiness Level
TU	Translate up
Und	Undo
VR	Virtual Reality
WIMP	Windows Icon Menu Pointer
ZI	Zoom in
ZO	Zoom out
Zoom	Zoom

Glossary

Term	Definition
3D Sketching	Sketching in the 3D environment. Either full 3D sketching or 2D sketching that is then used as a basis to extrude into a 3D shape, or a mix of both.
Adaptors	Gestures like headshaking or quickly moving one's leg that are unconscious and used to release body tension.
Bimanual asymmetric gestures	Gestures performed using two hands, where hands have different forms and follow different paths.
Bimanual symmetric gestures	Gestures performed using two hands, where hands are mirror images of each other.
Bounded ideation	Happens when designers focus on CAED tools and how to use them rather than ideation.
Circumscribed thinking	Happens when the design is limited by the tools capabilities, or with what designers find easiest to do with available tools.
Cohesive gestures (or catchments)	Gestures that are thematically related, but temporally separated, where a continuation of a specific theme after the speaker was interrupted is characterised by the recurrence of a gesture.
Conditionally free gestures	Gestures elicited from the system users, then prescribed for the future users.
Consensus set	A collection of gestures which were repeated by a significant number of participants (created following a statistical analysis checking for likelihood of gesture performance by chance for a specific activity).
Deictic gestures	Pointing gestures, used to indicate the direction of intended movement, or a direction of manipulation. Depending on the context and the direction of pointing, they can also have assigned meaning.
Dynamic gestures	Gestures that change over time, and a hand moves between a number of positions to form a full gesture.
Feature Modelling	Adding and subtracting solid features similar to traditional CAED systems.
Free-form gestures	No prescription involved and users are free to perform any hand motions.
Gesture temporality	Describes gestures in the function of how their form changes with time
Haptics /Haptic interfaces	Interfaces that rely on applying tactile sensation and control in order to interact with computer applications, allowing users to feel contact force.
Iconic gestures	Gestures that represent meaning closely related to the semantic content of the speech and illustrate what is being said e.g. a person discussing an object rolling down a hill would perform a rolling motion using their hands.

Term	Definition
Imitation gestures	Free-form gestures where hand motion performed was copied into the system exactly as performed, unable to support symbolic input.
In-air gestures	Gestures performed in unrestricted three-dimensional space.
Manipulative gestures	Gestures that interact with and modify a spatial component of an object in an interface.
Metaphoric gestures	Iconic gestures which represent abstract content e.g. a cutting gesture to indicate a decision has been made.
Modalizing symbolic gestures (or speech linked gestures)	Gestures that primarily complement speech e.g. a person asking "'Have you seen her husband?' while holding their hands apart would indicate he is overweight".
Object creation	Refers to visualisation of the object shape in a virtual environment.
Object manipulation	Refers to activities such as rotation, translation, zooming; changing the viewpoint without actually changing the object shape in a virtual environment.
Object modification	Refers to activities focused on object shape change e.g. subtraction, addition, distortion in a virtual environment.
Pantomimic gestures	Gestures that represent familiar concepts, but they are imitations of what is being implied e.g. motioning 'lighting up' of a cigarette to ask for a lighter.
Premature fixation	Design ideas that are not fully developed may appear final earlier than they actually are, owing to visualisation capabilities of the CAD software, and remain underdeveloped and not fully explored.
Prescribed gestures	Gestures defined prior to the use participants had to learn and perform accurately in order to interact with the system.
Recognisability	Recognisability is defined in terms of a function of an object in this thesis. A 3D object observed on a computer screen or in VR may have a specific function in physical world were observed. An object where a specific function it serves in a physical world can be easily determined by various individuals is considered to be recognisable. For example a mobile phone would typically be used to converse with people and would be held in a specific way against one's ear or in the palm of a hand if it was used for browsing/texting. The mobile phone would be considered a recognisable object. An irregularly shaped sphere does not have an easily identifiable function across various individuals. The irregular sphere would be considered a non-recognisable object.
Semaphoric gestures	Gestures used to trigger a predefined action, defined in a formalised dictionary and therefore require prior knowledge and learning.

Term	Definition
Sketch parsing	Division of sketches into their basic elements.
Static gestures	Also called postures. Have the same form for the entire duration of the gesture, and if a “snapshot” or them was taken it would not change over time.
Symbolic (or emblematic) gestures	Gestures that represent a symbolic object or concept, devoid of any morphological relation with what is being referred to. They have a direct translation into words, are used deliberately to send a particular message, and have a widely accepted meaning, albeit one that may be specific to a group, class or culture. e.g. “thumbs up” to indicate approval, hand waving as a greeting.
Unimanual gestures	Gestures performed by one hand.
Virtual Sculpting/Surface Modification	Refers to the modification of shape in a virtual environment applied through surface modification, often emulating traditional sculpting.
Wizard of Oz	User based research approach where the response to a participant’s action is emulated by study designer to confirm to the participant that their activities are implemented and acceptable.

1. Introduction

Hand gestures are motions performed by a human's hand. For simplicity, hand gestures will be referred to as gestures in the remainder of this thesis, although generally gestures can also include arms, or full body. Gesture research is present in the field of Human Computer Interfaces (HCI), where exploration of gestures is tied to communication between the human and the machine. It is also present in linguistics and social sciences, where the focus is exploration of communication between humans and cultural impacts of gestures. In design, gestures have mostly been observed in terms of teamwork and their relation to an object being designed. This introduction sets out the scope of the work of this thesis and defines the research's aim and objectives. It will provide information on the research methodology followed throughout, and clarify the thesis structure.

1.1. Scope of work

This sub-section will position the research, and define its scope. It will define where user-based research of gestures for conceptual design sits within the field of engineering design and its design phases. Types of design process the conceptual design is performed in will be defined, along with the goal of the activities gestures will be elicited for, and the role of those gestures. Then the fundamental differences between thinking required for conceptual design and structured interaction required for use of CAED systems will be described, clarifying why CAED systems currently do not support conceptual design. The need for user-elicited vocabulary of gestures for conceptual design will be set out. Then collaborative and individual conceptual design activities are compared, the ways gestures are used in them, and the decision to focus on an individual engaging in conceptual design is justified.

Conceptual design is the initial stage of the design process, during which fundamental, but approximate, outlines and form of a product are created, before the design specification is fully defined and frozen (Keinonen and Takala (2010), pg 17; Ulrich and Eppinger (2011), pg 18). During concept generation and evolution changes are frequent (Zhong et al., 2011), and design ideas can, and are often encouraged to be, vague and incomplete, until they are sufficiently developed (Müller et al., 2003, Company et al., 2009). Often the ability to generate or modify a design at a pace that matches the designers thinking processes is more important than to focus on detail (Fuge et al., 2012). Details, dimensions and constraints only become necessary in the detailed design stage. The focus of this thesis is concept generation.

The design process can be routine, innovative or creative; ranging from known structure, known basic structure to unknown structure (Goel et al., 2012). Conceptual design is for the most part *creative and its structure is often unknown*. Creative design strategies can be problem-oriented (aim to improve a product), function-oriented (build a product to perform a specific function), product-oriented (secondary function needs improvement) and form-oriented (changing the shape and format of a design) (Li et al., 2007). In the initial stage of conceptual product design, the form of an object has to be defined before any other strategies are employed to solve a problem, achieve a function or improve a product. Products created as an outcome of a design activity can introduce minor modifications to existing designs, differ from the starting design significantly, or be entirely new designs where existing design is used as input (Haik and Shahin, 2010). Conceptual design is performed for all three types of design activities, and in this thesis differentiation between these three types of designing was not made. Hand gestures are elicited for *object creation, modification and manipulation*.

Gestures are explored in HCI (Billinghurst, 2018), but the primary theoretical underpinnings for the gesture use and meaning come from social sciences and linguistics (Kendon, 1988, McNeill, 1992, Quek, 2004). In linguistics, gestures are often seen as a way to replace or supplement verbal communication, and come with cultural implications. Gestures explored in this thesis perform a communicative role; however, the manner in which this communication is performed can differ significantly from the linguistic definitions of gestures. During design, designs are sometimes drawn without any spoken reference, illustrating the need to consider gestures without speech as well (Liikkanen and Perttula, 2009). The gesture communication observed focuses on ways to *convey a form of a shape and modify or manipulate it*.

Computer Aided Engineering Design (CAED) tools are widely used for engineering design and manufacture in industry and successfully support and interlink detailed design (supported by Computer Aided Design or CAD), analysis and simulation (supported by Computer Aided Engineering or CAE), and manufacturing (supported by Computer Aided Manufacturing or CAM) (Gao et al., 2000, Fuge et al., 2012). CAD, CAM and CAE are the key elements of CAED. Typically, the use of CAD starts when detailed design begins. It is believed that CAD is generally not used during conceptual product design because commercially used CAD systems do not have sufficient functionality to support conceptual design (Verstijnen et al., 1998a). While computers are good at automating processes (Horváth, 2000), the type of concrete, precise and quantitative information commercial CAD systems require as an input (Zhong et al., 2011) is usually not available at the conceptual design stage, when specifications and constraints are often not fully established (Igwe et al., 2008). Vague and unfinished ideas that are evolved during the conceptual design process cannot be supported by the capabilities of current CAD systems (Alcaide-Marzal et al., 2013, Shesh and Chen, 2004), as computational techniques supporting them do not fully fit them (Liddament, 1999). Complex interfaces used to interact with CAD systems are not compatible with the conceptual design process (Fuge et al., 2012), as they detach sequential activities and do not include intuitive modes of interaction (Stark et al., 2010). Use of CAD has been found to interrupt the designers thinking, as instead of thinking about the design they tend to focus on commands and procedures used in CAD for specific shape creation (Huang, 2007). The work reported in this thesis was inspired by the lack of computational support for conceptual design, and while it does not aim to explore gestures for CAD implementation specifically, recent developments in Augmented Reality (AR) and Virtual Reality (VR) technology have served as inspiration. While in-air gestures for conceptual design explored do not target CAD directly, it is envisaged they may be used in CAD to complete the process and allow uninterrupted progression from requirements and conceptual design, through to detailed design, embodiment, simulations and manufacture to the final product.

Expansion in numbers of applications incorporating hand gestures seems to coincide with technology developments that have occurred in the past decade (Vuletic et al., 2019). Introduction of sensors which can accurately detect users hands performing gestures in 3D space such as Kinect (Kinect, 2018), LEAP (LEAP MOTION INC., 2018), Azure Kinect DK (Azure Kinect DK, 2020), Orbbec (Orbbec, 2020), Ultraleap (Ultraleap, 2020), Intel RealSense (Intel Realsense, 2020) etc. They are relatively cheap, portable and supported by Software Development Kits (SDKs) which provide shared databases and thus simplify hand detection and recognition by reducing the need for development of independent algorithms for every step in the process. A drawback of the applications inspired by technological developments has been that often the gestures used are those that are easily recognisable by a specific system (Schmidt, 2015). While existing gesture based interaction systems for design typically do not focus on conceptual design specifically, but design overall, they explore shape creation, modification and manipulation, which are an inherent part of conceptual design. Majority of the applications used free-form gestures for the creation of splines or surfaces that build up a 3D model, while using simple prescribed gestures such as pinch or hand grasp to perform activities such as element selection for example (Chu et al., 1997, Buchmann et al., 2004, Kim et al., 2005, Robinson et al., 2007, Holz and Wilson, 2011, Vinayak et al., 2013, Han and Han, 2014, Arroyave-Tobón et al., 2015, Vinayak and Ramani, 2015). In some applications prescribed gestures are used for shape creation, for example a cylinder is created by drawing a circular profile using an index finger, that is then swept to extrude it in space along a path following the same index finger (Vinayak et al., 2013, Huang et al., 2018). They could then be further modified using free-form and parametric deformation, by pinching and pulling the shape elements. While the user feedback was collected when these applications were tested, it focused on the ease of use, and not on the appropriateness of the gestures for the activities they were used for. The researchers in the field acknowledge that studies are required that will identify the most natural and intuitive hand gestures (Huang et al., 2019). Therefore, in this research the technology that may be used to eventually implement future interfaces is not considered, and it is separated from the gesture elicitation process. Decoupling of technology from the gesture elicitation process ensures the onus is on the appropriateness of gestures for the design activity, and provides inputs to guide future interface and technology development. The research in this thesis aims to identify the most natural, intuitive and suitable gestures for conceptual design in three-dimensional world without technical limitations. However, the technology has served as inspiration for the type of gestures explored. The gestures explored in this thesis are natural and intuitive in-air *gestures used to generate a form or an outline of an object*. While the technology is decoupled from the decisions about the most appropriate gestures for the task, the existence of the technology that could eventually be used for implementation was one of the drivers for the research.

Gestures used in existing applications for HCI interaction in general, are typically defined by the researchers developing the studies, often due to ease of application or alignment with the technology used (Piumsomboon et al., 2013, Huang et al., 2018). One design based study has been identified which focused on user elicited gestures and reached the application stage (Jahani and Kavakli, 2018), but it resulted in high level findings that do not explicitly identify specific hand gestures and the application tested diverged into car comfort control interfaces. In the field of HCI, user-based gesture elicitation has been explored for AR environments (Piumsomboon et al., 2013), TV control (Dong et al., 2015, Dim et al., 2016), and 3D CAD modelling in conceptual design (Khan and Tunçer, 2019). Methodologies followed in them were variations of the methodology developed by Wobbrock et al. (2009) and Morris et al. (2010), focusing on exploring the most appropriate gestures for surface technology based interaction. Gestures are typically elicited from inexperienced users, in order to identify the most universally appropriate gestures. Similarly to the goal of this thesis, the elicitation process is separated from the technology that may be used during the implementation stage. This is done to elicit the most appropriate gestures that are not limited by current capabilities of available technology. In practice, this means the “Wizard of Oz” approach is used, where users propose gestures prompted by referents shown to them, and users’ propositions are always made acceptable via a response emulated by the study designer/facilitator to confirm this acceptance to the users, regardless of actual technical capabilities of a system facilitating the gesture implementation (Lee and Billinghurst, 2008). There have been no studies exploring user-elicited gestures for conceptual design in isolation from the technology that may be used to support it, and this is the gap this thesis is aiming to address.

User-elicited gestures for collaborative designing have been explored in the past. For example, studies have been conducted that observe designers working in a team e.g. observing gestures as a communication channel linked to learning during group work (Eris et al., 2014) or their role in terms of communication of design concepts with regards to their directionality and Function-Behaviour-Structure elements (Cash and Maier, 2016). While collaboration is an important aspect of design, designers do not always work in groups, and even within groups have discrete activities that do not focus on group interaction at all times. More importantly, even during group work, it is essential that individual designers are able to create a form and interact with it (Cash and Maier, 2016). This is a prerequisite for further collaboration. While both teamwork and individual activities are inherent elements of conceptual design, the approaches for their explorations are very different and focus on different aspects of conceptual design. The scope of this thesis is to *observe a single designer working on their own, as this is the first step of the concept generation.*

In summary, this thesis focuses on user elicited in-air hand gestures for concept generation, of an individual designer, working during the conceptual design stage of the industrial engineering design process. Gestures are observed in isolation from potential technology used for their implementation.

1.2. Research aim and objectives

The aim of this thesis is to identify a gesture vocabulary of natural and intuitive gestures designers would employ during form creation within a product design process if gestures were a sole mode of interaction. In the remainder of this thesis, this vocabulary will be referred to as “gesture vocabulary for form creation”, for simplicity. As it will be further discussed in Section 4, it is not envisaged that gestures will be a sole mode of interaction, and the questions of what the best combination of modalities would be optimal is out of the scope of this thesis. However, exploration of hand gestures in isolation from other modalities is targeted in order to identify the activities that designers consistently perform same gestures for. This aim will be reached through a number of objectives:

Objective 1: Provide an overview of existing approaches to support for conceptual design via a literature review

Objective 2: Provide an overview of gesture use for applications focusing on design via a literature review

Objective 3: Define a knowledge gap based on the outcomes of Objective 1 and Objective 2

Objective 4: Define the methodology that will be followed in the study performed to identify the vocabulary of hand gestures for conceptual design

Objective 5: Perform the study and build the vocabulary of hand gestures for conceptual design

Objective 6: Evaluate the vocabulary of hand gestures for conceptual design

Objective 7: Test the study robustness

Objective 8: Discus research outcomes, its strengths and weaknesses and future work.

More detailed objectives and tasks for the research based on the literature review findings will be given in Section 4.4.

1.3. Research methodology aim and objectives

In order to follow a scientific process and remain as objective as possible, development of knowledge has been guided by a research philosophy. The nature of the research performed was inextricably linked to inputs from study participants, effectively their opinions, and this would place the nature of this research within the space of critical realism. However, the nature of design studies and data collection methods typically performed in them aligned better with basic beliefs, focuses and aims of positivism or realism. Hence, positivism, realism and critical realism, their beliefs and methods have been reviewed in Table 1-1 providing comparisons and highlighting the approaches taken in this research. Elements elected to include in the mixed philosophy followed in this study are denoted by bold font and shaded cells in Table 1-1 .

Basic beliefs followed in this thesis are positivistic, the world is external and objective, the observer is independent and science is value free and not driven by human interests. However, the aim of the author is not to look for causality and fundamental laws, but to understand what is happening and develop ideas through induction from data via empirical research. Hypotheses are not set prior to research commencing, instead collected data is analysed and an inductive research mode is followed (Saunders et al., 2012). The methods used are mixed, and while the studies are developed so the outcomes can be measured, both qualitative and quantitative methods are used. While positivism claims to be able to discern the reality via observation as a sole applied technique, here methodological rigour and triangulation from multiple data sources are hoped to approximate the objective reality and generalise findings (Fox, 2008), which is closer aligned with realism. There are elements of critical realism research philosophy that were followed, particularly in terms of the world being external and as objective as possible, as it was still constructed from study participants' perspectives and experiences. However, critical realism does not fully describe the approach taken as causation was not aimed to be identified and application of theory was not one of major goals of the research, although it was done in specific instances where appropriate. Therefore, research philosophy followed in this thesis is a mix of positivism and realism (a variant of post-positivism), with elements of critical realism.

Research strategy employed are studies designed to allow for observation or designers' natural activities in set conditions and environment. Time horizon is cross sectional, as each participant only performed the activities once, and was not followed through time.

Table 1-1 : Features of positivist, relativist and critical realism paradigms used as a mixed approach in this thesis

Theme		**Positivism (Amaratunga et al., 2002)**	**Realism (Amaratunga et al., 2002)**	**Critical realism (Danermark et al., 2019, Tsang, 2014, Edwards et al., 2014, Tsang and Kwan, 1999)**
Basic beliefs	The world is:	**External and objective.**	Socially constructed and subjective.	**External, but constructed from our perspectives and experiences.**
	Observer is:	**Independent.**	Part of what is being observed.	Explanatory power must be upheld outside of observable knowledge of specific events.
	Science is:	**Value free.**	Driven by human interests.	**Value free.**
Researcher should	Focus on:	Facts.	Meanings.	Interpreted facts.
	Aim to:	Look for causality and fundamental laws.	**Understand what is happening.**	**Understand what is happening by interpreting causes and structures generating the observable events.**
		Reduce phenomena to simplest elements.	Look at the totality of each situation.	Distinguish between causes, events and what we can know about events.
		Formulate hypotheses and test them.	**Develop ideas through induction from data.**	Understand the structures that generate events.
Preferred methods		**Operationalising concepts so that they can be measured**.	**Using multiple methods to establish different views of the phenomena.**	**Using multiple methods to establish different views of the phenomena, often case studies**.
		Takin large samples.	Small samples investigated in depth over time.	Samples can be large or small depending on the field.

These choices are illustrated using thick connecting line in the graph in Figure 1-1 showing the frameworks of research methodology, adapted from Buckley et al. (1976).

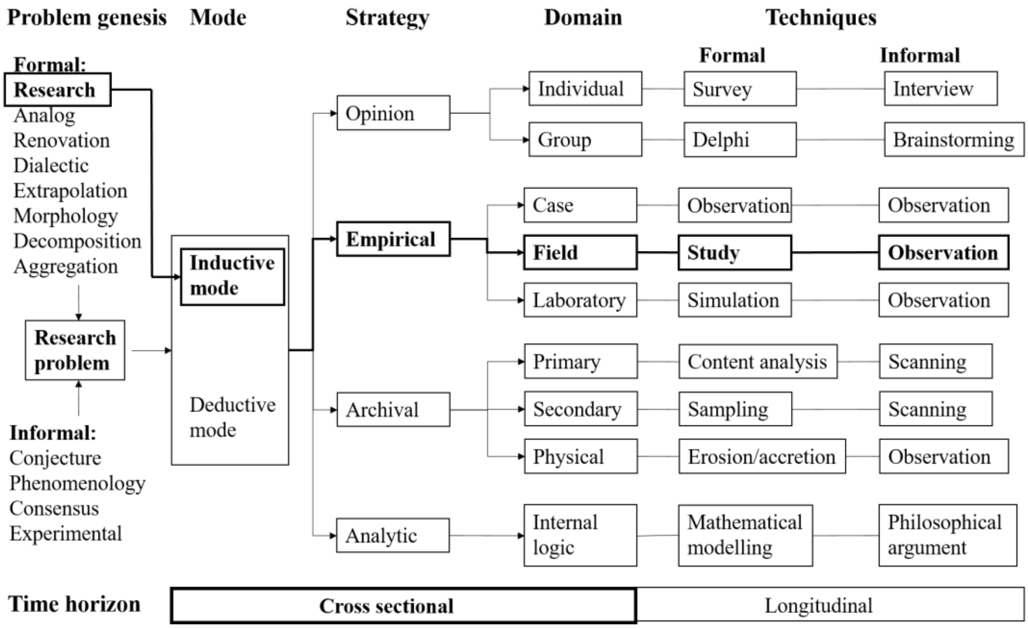


Figure 1-1 : Research philosophy, mode, strategy, domain and techniques followed in this thesis (adapted from (Buckley et al., 1976)

Data collection methods are observation (via recordings made), and post study questionnaires. Per guidance by Ryan (2006) quantitative data collected via observation is used to observe patterns across many cases, show that the findings are numerically significant, and provide readily available and unambiguous information that findings can be deducted from. A mix of quantitative and qualitative data provided via questionnaires seeks to provide a comprehensive view, extract quantitative data and it relies on people’s words as its primary data.

To supplement the research methodology with a more structured approach specific to the field of design, the research approach for design tool development developed by Duffy and O'Donnell (1999) was adapted and followed in this thesis. It was developed to act as an overall guide to conducting the work performed in order to “develop design systems and provide a basis upon which to introduce hypothetical design practice” (Duffy and O'Donnell, 1999), and as such thematically fits this research well. While a developed system is not an objective of this thesis, its findings aim to inform future system development to enhance the conceptual design process.

On the other hand, the approach does not prescribe the strategies, domains or techniques to be used, but it does provide additional structure to the chosen philosophical approach.

Visual representation of the research methodology in terms of phases of research, research outcomes and resources can be seen in Figure 1-2, adapted from Duffy and O'Donnell (1999) and Tenneti (2007).

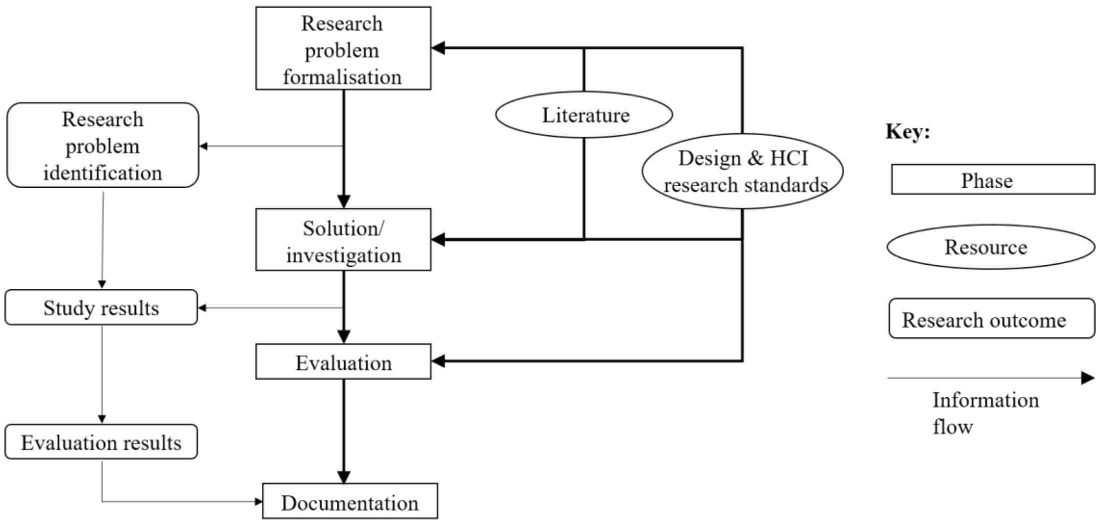


Figure 1-2 : Sequential structure of research phases, resources and outcomes (adapted from Duffy and O'Donnell (1999) and Tenneti (2007)

Research problem formalisation relies on findings from the literature review of the conceptual design field, and the review of design and HCI research practices, and results in the identification of a research problem. The research problem is then investigated via a study designed to provide sufficient quantity of data, which is then quantitatively and qualitatively analysed, and its outcome are study results. These are then evaluated in order to establish if the results of the study are effective and valid. Finally, the results are documented.

1.4. Thesis structure

This chapter concludes with the presentation of the structure for the remainder of this thesis illustrated in Figure 1-3.

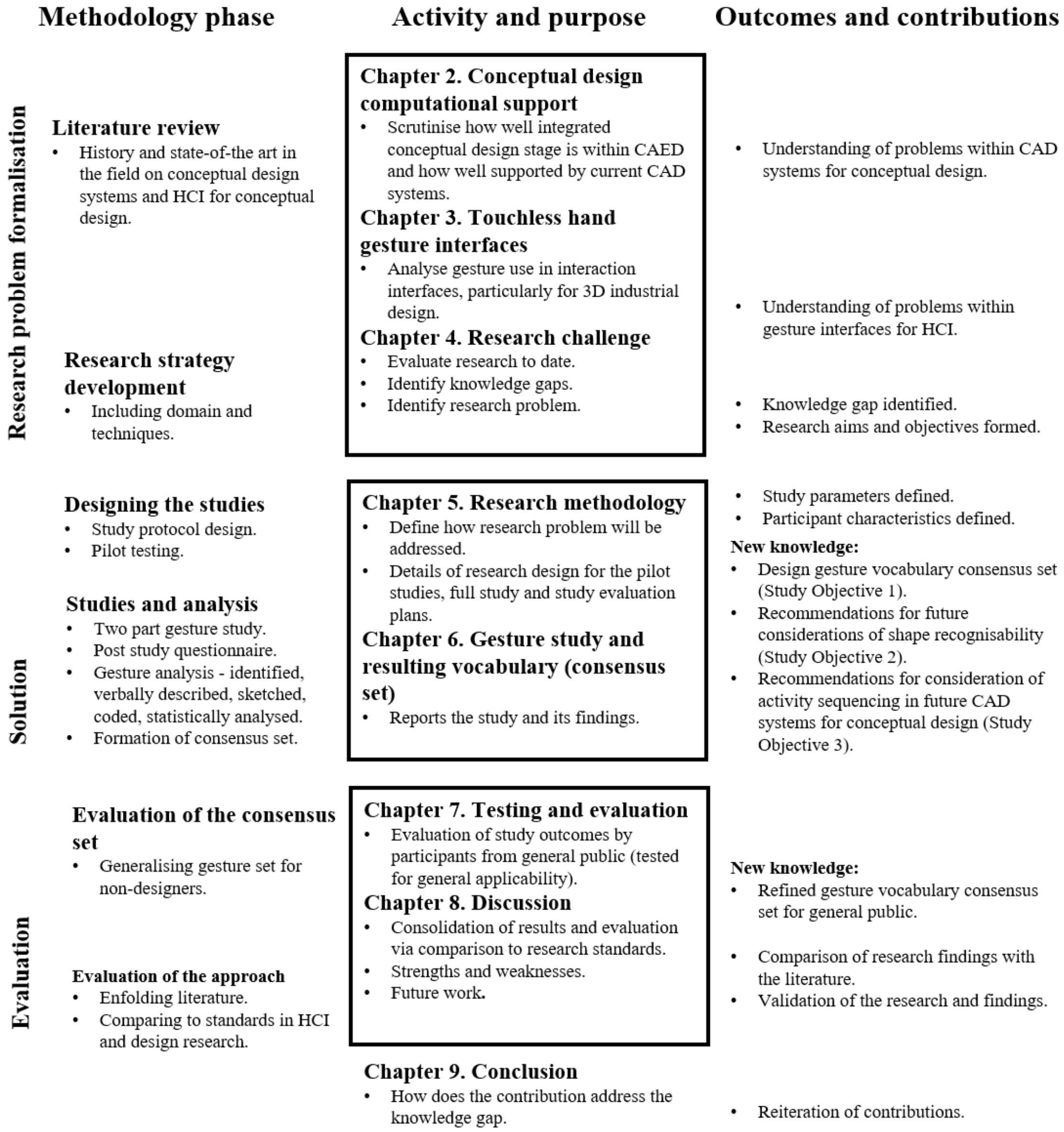


Figure 1-3 : Visualisation of the thesis structure, linked to the methodology phases and outcomes and contributions

Research problem formalisation is covered by Chapters 2, 3 and 4. Chapter 2 provides and overview of the currently available computational support for conceptual design. Chapter 3 analyses use of gestures in interaction interfaces, with particular focus on design. Chapter 4 critically analyses the findings of the previous two chapters and identifies the knowledge gap. Chapter 5 defines the methodology that will be followed in the study reported in Chapter 6. Chapter 6 also reports the analysis of the findings and the resulting vocabulary of hand gestures for selected activities performed during conceptual design. Evaluation of the vocabulary by a different group of non-designer participants and testing of the study approach is reported in Chapter 7. Evaluation of the research and its approaches are discussed in Chapter 8. The thesis ends with a conclusion given in Chapter 9.

2. Conceptual design computational support

This chapter will explore the relationship between conceptual design and *Computer Aided Engineering Design (CAED)*. The term CAED is used here in the widest sense, to cover the computational support for conceptual design. The chapter will cover the history of CAED use in design (definitions of CAED and CAD used in this thesis are given in Section 1.1), characteristics of the conceptual design stage and challenges it introduces to CAED, and provide an overview of the support for conceptual design provided by current CAD systems. CAD systems are focusing on the creation of the shape of the product being designed, and majority of the solutions reviewed do fall under this category. However, some solutions cross over into the wider CAED, and are also included. Then benefits and drawbacks of current CAD systems will be reviewed, and existing CAD systems developed to support the conceptual design stage will be classified.

The objective is to scrutinise how well integrated conceptual design stage is within CAED and how well supported by current CAD systems. This will provide an *overview of existing approaches to support for conceptual design.*

2.1. CAED and design

Computer Aided Engineering Design tools are widely used for engineering design and manufacture in industry and successfully support and interlink detailed design, analysis, simulation and manufacturing (Gao et al., 2000, Fuge et al., 2012). They are continually improving, but their use typically starts during detailed design, and conceptual design is not generally performed using CAD systems. It is believed this is because commercially used CAD systems do not have a built in functionality to support conceptual design (Verstijnen et al., 1998a).

Academic research on conceptual CAED is exhaustive, but has not been adopted by the industry (Horváth, 2000), which typically allows conceptual design to be performed as conceptual design team and individual designers in it see fit (Keinonen and Takala, 2010, pg 64-65) and relying on their experience (Macmillan et al., 2001), rather than invest in a systemic solution integrated with their processes (Horváth, 2000). This chapter will explore the reasons behind why CAED systems are not used for conceptual design, analyse the developments for conceptual CAED in terms of both design process and human computer interfaces supporting it. The content in this chapter is based on a literature review published by the author[1].

2.1.1. Support evolution

The first instance of CAD system research appeared in the literature in the 60s (Sutherland, 1964), but the adoption in the industry really started during the 80s (Liker et al., 1992), with a nearly eight fold increase between 1980 and 1988. The first instance of CAD software reported on by Sutherland (1964) used a light pen that could draw in 2D, copy, paste and delete. He argued that drawing was a type of designing in itself. Early CAD systems advocated for the need of 3D models in the context of the assembly and the associated information providing more complete representation of form, geometry and dimensions (Kjellberg and Kjellberg, 1984).

At times CAD systems were found complex and difficult to use, especially if they included knowledge-based systems supporting creativity, which at times also required learning of a new dedicated language (Rouse, 1989). Over time CAD systems transformed from a primarily 2D into 3D systems, supported by a number of developments such as adoption of the solid modelling developed by Alan Grayer, Charles Lang, and Ian Braid (Elliott, 1989), and NURBS (Non-Uniform Rational B-

[1] Vuletic, T., Duffy, A., Hay, L., McTeague, C., Pidgeon, L. and Grealy, M., 2018. The challenges in computer supported conceptual engineering design. *Computers in Industry*, *95*, pp.22-37. https://doi.org/10.1016/j.compind.2017.11.003

Spline) developed by Ken Versprille (Rogers, 2000) in the late 80s and early 90s. By the time surfacing and free-form shapes were integrated with CAD, it started being perceived as an increasingly important tool that can support manufacturing considerations, aesthetics and ergonomics (Kimura, 1997).

However most CAD applications had a high degree of specialisation and fragmentation, and were underutilised overall, as specific groups of staff used specific modules in their work (Liker et al., 1992). At the time, the additional problem was that some software only worked on specific workstations it was developed for, and was delivered with (Rouse, 1989). This made it less attractive for industry. A need for standardisation and hardware independent software was recognised early, and ISO (International Organisation for Standardisation) norms for supporting systems were developed (Hensel, 1986). However early on, conceptual design was not the focus of the systems, and it was acknowledged that conceptual design was “only supported in 2D and dimension driven which does not correspond to how designers design” (Rouse, 1989). The ability to design in 3D, when achieved, was hoped to lead to better representation of form, but conceptual design was not specifically considered, and development of commercial software focused on detailed design, which digitalises well-defined, dimensioned and finalised shapes (Black, 1996).

2.1.2. Disparity between the characteristics of computational support and conceptual design stage

“Conceptual design refers to the fundamental outlining of a product carried out during the first phases of product creation or at least before the design specification is frozen” (Keinonen and Takala, 2010, pg 17). It can also be described as “approximate description of the technology, working principles, and form of the product” (Ulrich and Eppinger, 2011). A definitive aim of mechanical conceptual design is to allow users to develop design alternatives in the form of virtual or design prototypes (KULCSÁR et al., 1995). It typically consists of three stages: background research, concept generation and concept evaluation (Keinonen and Takala, 2010, pg 60).

During the concept generation, the design is evolving and changing frequently (Zhong et al., 2011). The need to generate and manipulate ideas quickly takes priority over the focus on detail (Fuge et al., 2012). Initial designs are created that are then modified or combined to create concept variants that comply with the design requirements, defined either by customers or the context of the product being designed (Zheng et al., 2001, Müller et al., 2003). Design continually evolves, and the design metamorphosis characterises a design activity (Liddament, 1999). Gradually design turns from a hazy, unfocused perception, into focus and gains more detail (Tovey, 1997). Modelling using 3D commercial CAD systems requires concrete, precise and quantitative information as an input (Zhong et al., 2011). This is not always available at the conceptual design stage, when specifications and constraints are often not fully established (Igwe et al., 2008). Early on, designers focus on overall appearance of the model, and the exact dimensions, positions, tolerances, and similar quantified qualifiers become important later, during detailed design (Sharma et al., 2011). Some researchers believe that design concepts are inherently uncertain and incomplete (Varga et al., 2007), and that this ambiguity can contribute to design emergence (Evans, 2005). This means that, during conceptual design, it is beneficial to keep design ideas vague and incomplete, until they are sufficiently developed (Müller et al., 2003, Company et al., 2009).

2.1.3. Implementation barriers

Computers are good at automating processes, but conceptual design usually does not provide enough information in a suitable format and has too many varied parameters to allow for successful automation (Horváth, 2000). Capabilities of current CAD systems cannot provide adequate support for the manipulation of graphical data to the degree required to enable maintenance of vague, unfinished ideas (Alcaide-Marzal et al., 2013, Shesh and Chen, 2004). The computational techniques provide powerful design tools, but they do not fully fit design activities performed during conceptual design (Liddament, 1999). Some authors describe this dichotomy as the distinction between the subjective realm of the design and its designer defining the form, and the objective realm of tools used to create the shape (Madrazo, 1999).

Additionally, complex interfaces used to interact with CAD systems are not suitable for conceptual design (Fuge et al., 2012), as they detach sequential activities and do not include intuitive modes of interaction (Stark et al., 2010). Commercially available CAD systems rely on a menu based WIMP (Window Icons Menus Pointer) interface (Sharma et al., 2011, Zhong et al., 2011), and in this thesis it will be referred to as traditional human computer interface for CAD. A WIMP interface requires extensive training for the user to internalise a large number of tools and procedures. The learning curve is steep and new users find the process of using the mouse and keyboard in a 2D environment to design a 3D object tedious, lengthy and unintuitive (Dave et al., 2013, Gao et al., 2000, Zhong et al., 2011). Finally, the CAD terminology does not always match the engineering design terminology (Wingård et al., 1992). Even when procedures and processes are adopted by the users, some design activities such as free-form spline modelling or modification (used to design complex irregular shapes), require manipulation of splines via a large number of control vertices, requiring large amounts of time and effort (IX et al., 2001). There is a lack of appropriate interfaces to enable computer tools for designing rather than modelling, as computer's logic and human logic are not always compatible (Madrazo, 1999).

New interaction mechanisms are required to make CAED systems easier and more intuitive to use (Rodriguez Esquivel et al., 2014), and they need to incorporate natural human actions (Verma and Rai, 2013, Shankar and Rai, 2014, Ye et al., 2006). Various alternative human computer interface (HCI) solutions are now being considered to enable more effective communication between the user and the CAD system (Esfahani and Sundararajan, 2012), such as gesture based interface, VR (Virtual Reality) supported interfaces, or haptic interfaces.

Characteristics of the users interacting with the CAD systems are a significant parameter, and user experience is one of the key characteristics required for successful deployment of currently commercially used CAD systems (Dadi et al., 2014). During CAD interface development user experience was considered largely in the interface evaluation stage, potentially leading to user-sourced requirements for conceptual design not being captured (Vuletic et al., 2018b). Recent academic research attempts to overcome this limitation, and systems that could be quickly mastered regardless of experience levels of the users are explored, albeit still in early stages of development (Lawson, 2005, Mayda and Börklü, 2014).

As early as 1983 there were reports of industry not adopting systems developed by academia, although they were mature enough. It was believed that this was due to a wide range of the systems and lack of willingness to invest resources to transform them to fully fit the industry needs (Denhaa, 1983). CAD implementation can also require change in the organisational structure, leading to lower levels of adoption (Liker et al., 1992).

2.2. General design support

While CAED systems have developed greatly since their introduction, the WIMP interface is still the most commonly used interface, and it does not fully support conceptual design activities (Kazi et al., 2017). Ways of expanding CAED to include early stages of design are continuously explored, but CAED is still primarily used in detailed design, analysis, simulation and manufacture.

Sketching using pen and paper is still very common in conceptual design (Goldschmidt, 2017), as is clay and foam modelling, which allows designers to better understand ergonomic features, compared to the digital form (Alcaide-Marzal et al., 2013, Arora et al., 2017, Ranscombe and Bissett-Johnson, 2017). Having a physical model allows the designers to control and manipulate it while avoiding premature focus on detailed design, and instead including uncertainty and ambiguity that are missing from CAED (Kazi et al., 2017). This means that sketches and models later need to be reproduced in CAD to enable digital manufacturing (Ranscombe and Bissett-Johnson, 2017), which is a time consuming and error-prone process (Kang et al., 2019).

The "lack of 3D geometric information in sketches and the imprecision associated with them makes them difficult to interpret algorithmically" and automate the process (Shesh and Chen, 2004). CAD systems largely support a sequential structure that does not have many similarities with unstructured and changing creative activities performed during conceptual design (Igwe et al., 2008).

2.2.1. Benefits of CAD systems in supporting conceptual design

The nature of CAD systems has changed over time, as they are now moving towards a more intuitive and seamless interaction. However, the key reason CAD is still used is it tends to provide faster and more accurate solutions, and accurately capture detailed design information (Hartman, 2009). Fully extending CAD to the conceptual design stage would mean it would become more efficient and effective and benefit from integration with detailed design, analysis and manufacturing. Academic research exploring conceptual CAD, while not adopted by the industry yet (Horváth, 2000), has identified areas where conceptual CAD could bring significant benefits. It introduces enhanced visualisation and communication, better group creativity and allows more time to be spent on ideas rather than detail (Robertson et al., 2007, Robertson and Radcliffe, 2009). 3D sketching was found to improve perception of spatial features and enhance discovery of spatial features and relationships, along with improving designers' problem finding behaviours (Rahimian and Ibrahim, 2011).

2.2.2. Drawbacks of CAD systems in supporting conceptual design

Speed and accuracy of capture are not always improved by the use of CAD in the conceptual design stage. WIMP interface lacks high-level shape operators that are necessary for designing and modifying model shapes that are required for conceptual design (Zheng et al., 2001, Gao et al., 2000). Additionally, modification of fine details of surfaces of 3D models can be a difficult and time-consuming process (Gao and Gibson, 2006). In some domains, customers may take part in evaluation of product design concepts, and it is difficult for them to communicate their change intention for a product through commercially available CAD systems (Zhen-yu and Jian-rong, 2005).

When current CAD is used in the conceptual design stage, it is sometimes found to be used prematurely, leading to effects such as circumscribed thinking, premature fixation and bounded ideation (Veisz et al., 2012). Circumscribed thinking is when the design is limited by the tools' capabilities, or with what designers find easiest to do with available tools (when it prevents designers proficient in CAD from introducing unnecessary complexity and wasting resources it can be considered to be positive) (Robertson et al., 2007, Robertson and Radcliffe, 2009, Musta'amal et al., 2008). Design ideas that are not fully developed may appear final earlier than they actually are, owing to visualisation capabilities of the CAD software, and remain underdeveloped and not fully explored – this is called premature fixation (Robertson and Radcliffe, 2009). Bounded ideation happens when designers focus on CAD tools and how to use them rather than ideation (Robertson et al., 2007, Robertson and Radcliffe, 2009). CAD tools require planning of steps required to build the model, rather than allowing full focus on form generation, causing extra cognitive load and a mismatch between design thinking and command manipulation (Huang, 2007). The result is often less creative outputs (Robertson et al., 2007, Robertson and Radcliffe, 2009).

To master the majority of CAD systems is a complex and time-consuming endeavour (Bodein et al., 2013). This is one of their largest drawbacks from the users' perspective. Studies have shown that even for simple 3D parts it took 16 weeks for the adoption of both procedural and declarative knowledge, providing five hours of instruction and additional practice on their own by the user weekly (Hamade et al., 2009). To reach levels of expertise required by the industry, the designers are often trained in CAD concurrently with their engineering design training, throughout higher education (Field, 2004). Often the knowledge required to use CAD systems is not intuitive or closely linked to the design process one would use if paper sketch or clay modelling were used.

2.3. Specific conceptual design support

While not adopted by the industry, research in CAD for conceptual design is prolific. Different research groups have taken different approaches in development of CAD systems for conceptual design stage. Some focus on meeting the requirements of the design process and design models, for example a certain level of abstraction required for conceptual design. Others are based on the use of new technology, either for display of designs (stereoscopic glasses or VR-helmets, monitor-based 3D display that directly tracks a single user's eyes and dynamically tweaks the image to achieve 3D effects, spherical 3D display that renders coloured volumetric elements that can be viewed from any angle), or new interaction technologies (3D mice, electronic pens, tablets with and tablets without digital screens) (Dickinson et al., 2005).

Inevitably, conceptual design approaches in different systems only cover elements of conceptual design, as they focus on a limited number of conceptual design requirements. CAD systems focusing on the design process will be discussed in Section 2.3.1, and those focused on HCI in Section 2.3.2. Both sections provide overviews of developments in their respective fields. The focus is on support for conceptual design implemented via computational systems. Features of the systems developed to support conceptual design were overviewed. When there was no clear differentiation in the systems encompassing both conceptual and detailed design, they were still included as conceptual design was included although not observed exclusively.

Articles reporting on conceptual CAD solutions contained a limited amount of information that could be used to provide comparison of effectiveness of the systems developed and traditional CAD systems, effectiveness of systems developed and analogue conceptual design approaches, or effectiveness of proposed HCI solutions compared to WIMP. Additionally, due to the vastly different approaches to conceptual design support between different categories, and HCIs developed for different systems, it was not feasible to compare them quantitatively, and they have instead been classified based on their focus and capabilities (Vuletic et al., 2018b).

2.3.1. CAD systems focusing on design process/models

The approaches to developing CAD for conceptual design will be classified into solutions focusing on modelling representations and solutions focusing on reasoning techniques, based on which element of conceptual design dominating the design process supported by the system was observed, as seen in Table 2-1. This classification is inspired by research by Hsu and Woon (1998). To deal with multifaceted and complex problem that is product design, requiring definition of function, behaviour and structure (Gero and Kannengiesser, 2014), they separate the modelling and reasoning aspects of the process. Hsu and Woon (1998) classified modelling representations based on computer needs vs human needs (languages, geometry models, graphs, objects, knowledge models, images), and reasoning techniques based on types of reasoning performed and whether the technique requires a large amount of data or is more procedural-oriented (data driven e.g. Neural networks, Case Based reasoning, Machine learning, Qualitative reasoning or knowledge driven e.g. Knowledge based, Optimisation, Value engineering).

Table 2-1 : Classification of computational systems supporting conceptual design focusing on design process/models

Modelling representation	Reasoning techniques
Sketch based	Data capture
Sketch parsing	Emergence
Surface modelling	Functional mapping
	Knowledge support

It should be noted that solutions based on reasoning techniques acknowledge the need for modelling representation, and sometimes implement elements of modelling representation, although modelling representation was not their key objective. Modern solutions focus on seamless integration of these aspects, rather than observing them in isolation.

2.3.1.1. Modelling representation

This section provides an overview of developments of CAD systems for conceptual design focusing on the modelling representation and includes sketch-based solutions, solutions based on sketch parsing, and feature based solutions.

2.3.1.1.1. Sketch based

Sketching is seen as a quintessential conceptual design activity and a number of CAD systems have attempted to adapt it to the digital environment. Externalising an idea can serve a communicative role, even if sketching is not necessary for generation of designs (Bilda, 2005).

Some prototypes focus on digitisation of 2D sketching using tablets, with added knowledge support provided during sketching (Hoeben and Stappers, 2005). Others provided the option of drawing 2D sketches onto the 3D models (Tovey and Owen, 2000). In an earlier incarnation, Tovey (1997) attempted sketch input into CAD via sketch mapping, sketch projection and sketch combination. The next step was provided by prototypes enabling 2D sketching in a software that recognised the shapes computationally and converted them into 3D models (Company et al., 2009, Jowers et al., 2008). Finally, 3D sketching in 3D space was explored (Müller et al., 2003, Dorta et al., 2008, Israel et al., 2009).

While these systems showed potential, they all required further development as none were at the point where they could be used commercially. They were typically developed for envisaged automotive applications requiring designs comprised of geometrically irregular shapes.

2.3.1.1.2. 2D Sketch parsing

An approach similar to sketching was sketch parsing, a division of sketches into their basic elements. In it 2D sketching prototypes are developed that parse and classify sketch elements on different levels of abstraction, while recognizing and maintaining spatial relations between sketch elements (Gross, 1996), or support restructuring and combining of elements (Verstijnen et al., 1998b). Both approaches tolerate ambiguity better than traditional CAD systems (Gross, 1996), and were aiming to support creativity (Verstijnen et al., 1998b).

2.3.1.1.3. Feature based

Feature based solutions endeavour to expand the current CAD systems with new capabilities, which support the conceptual design better. Different approaches were used to do this.

One solution transformed sketches into solids via sketch recognition, and different levels of abstractions were possible to achieve visualisation (Oh et al., 2006). Another focussed on retention of information about the design throughout different levels of abstraction supported by different feature representations (Brunetti and Golob, 2000). A solution by Kulcsar et al. (1995) focused primarily on mechanical design and proposed a CAD representation for conceptual design that allows linking of geometrical and physical attributes, through use of ports, representing physical connection and energy transfer, and initial geometry, represented as a mix of wireframes and contact surfaces. Finally, Hoffmann and Joan-Arinyo (1998) proposed a procedural mechanism for generation and deployment of a user-defined feature-based design paradigm. Users could choose a shape and size of the features, defined by a number of parameters, and then position and orient the features in a part they belong to.

2.3.1.2. Reasoning techniques

This section provides an overview of developments of CAD systems for conceptual design focusing on the reasoning techniques and includes solutions based on: data capture, supporting emergence, functional mapping and knowledge support.

2.3.1.2.1. Data capture

Data capture can be seen as an approach related to knowledge support, however it focuses on the events preceding the knowledge support and describes an approach to populating the databases knowledge support is based on. Sivanathan et al. (2015) developed and tested a framework that aimed to capture designers' knowledge and rationale throughout the design process, while attempting to retain high levels of abstraction required in conceptual design.

2.3.1.2.2. Emergence

Conceptual design is characterised by continuous development, vague representations and possibility for alternative interpretations. In this process, new designs emerge and Soufi and Edmonds (1996) explored, theoretically, how support for emergence could be incorporated into CAD supporting conceptual design. They argue that providing alternative descriptions of a pattern that emerges, via an interpretative process could be supported by computation easily. Using these patterns to prompt creation of new structures, what they call a transformational process, was deemed more difficult to achieve. Instead of fully automating the process computationally, they proposed supporting and augmenting a designers' creative process by providing an intermediate representation, achieved by decomposing the initial representation, allowing them to see more structures in an observed pattern.

Users would use gestures to indicate the position and shape of an emergent structure (pose matching) and to trace their outlines (curve tracing).

2.3.1.2.3. Functional mapping

Function is one of the three key descriptors of the design, and the approach focusing on functional relationships while considering modelling representation was attempted.

Gorti and Sriram (1996) mapped a logical description of an engineered system onto a physical description during conceptual design phase (called symbol form mapping). At this stage, components were not specified and connections were not fully defined. This approach decoupled the representation of spatial relationships from the generative capabilities of the system, as they were derived because of functional relationships, and represented as evolving descriptions of geometry. Bruno et al. (2003) similarly focused on the functional representation of the problem in conceptual design, ensuring a functional dataset was present through different levels of abstractions.

Al-Salka et al. (1998) based their approach on a Pahl and Beitz model, implementing it through a number of documents representing decompositions of a function that were linked together. It could be extended to other conceptual models, if they were defined in the internal language used. This approach allowed a designer to work on different design tasks in parallel, record the design history, capture statistical data about duration on the processes, and enable classification of different design problems.

2.3.1.2.4. Knowledge support for conceptual design

Knowledge based CAD systems endeavoured to allow the user to control the dynamics of interaction with the system (Shahin, 2008, Goel et al., 2012, Li et al., 2007, Bonnardel and Zenasni, 2010, Hertz, 1992, Ramscar et al., 1996).

For example, designers represent objects how they see them, and then the system compares the structures of the representation and the prototypical representation, where the relationship between the designer and the tool takes a form of non-pre specified dialogue (Ramscar et al., 1996). Two solutions allowed the system to suggest/generate a design based on historical elements, and then allowed the users to modify it (Krish, 2011, Mayda and Börklü, 2014). Knowledge bases or database management systems embedded in them were collating previous solutions or in some cases suggested biologically inspired designs. Biologically inspired designs have been popular in architecture, and may have potential for application in mechanical engineering. Regardless of the control mechanism, knowledge support took the form of searching through a database of families and items (Sharpe, 1995).

Earlier applications proposed knowledge support CAD systems based on text, due to the potential of restrictive visual representations had to stifle creativity (Lawson and Loke, 1997). This approach argued words might allow for inclusion of uncertainty, especially since CAD drawings are insufficiently conversational, and leave little room for contribution from the designer. It was also believed the drawings may have originally been produced as an outcome of a working tool for designers rather than to communicate ideas. The computer reminding designers of connections between the ideas enhanced creativity. Creative ideas emerged from the process of giving meaning and making interpretations. Rosenman et al. (1994) proposed that future research should focus on intent-driven search, which could discover shapes with potential to satisfy given criteria, by adding semantic information to syntactic information that is currently usually associated with CAD terms.

Some solutions tracked users' activities and suggested changes or augmentations for the design (Shahin, 2008, Li et al., 2007). Some included an FBS (Function-Behaviour-Structure) approach (Goel et al., 2012, Li et al., 2007) and some used TRIZ (Li et al., 2007, Mayda and Börklü, 2014, Sushkov et al., 1995) to support ideation, and attempt to guide a designer through a systematic process. TRIZ contained techniques for analysis of ill-defined initial situations and ability to extract key problems to be solved (Sushkov et al., 1995). An evolutionary approach provided a pool of population solutions, their elements could be combined and adapted, informed by specific design situations and generalised domain knowledge. A mechanism stored and retrieved design cases and grouped associated relevant design cases, design schemas and design prototypes together (Rosenman et al., 1994).

Shahin (2008) believed organising the information in a systematic way would help the designers focus on creative activities. Similarly, Candy (1997) explored ways to support creativity by providing access to knowledge as a set of constraints in the form of domain-specific rules that could be used to test and generate design ideas as they were being developed. Hertz (1992) proposed an expert system that helps a designer to correct the project while considering predicted deviations, leaving them more time to make creative decisions concerning the unpredictable deviations. Others focus on reduction of unwanted innovation, by including a database of constraints against which designs were continually checked while designed in CAD (for repeat design, variant design, innovative design and strategic design at different levels) (Culverhouse, 1995).

Knowledge based solutions also considered costs. Sharpe (1995) enhanced the database search with function costing analysis. Dürr and Schramm (1997) sourced the knowledge support feedback, based on features, from the manufacturing stage and also considered function. FMEA (Failure Mode and Effects Analysis) was one method used for a preventative feedback. Hori (1997) aimed to support creative design by turning focus on requirements definition supported by knowledge in the field, where user interacted with the concept space. System presented the user with the "concept space, and the designer could rearrange the elements that may lead to a change of strategy, abandonment strategy (giving up on unimportant requirements) or new design strategy (based on new elements)" (Hori, 1997).

Most knowledge-based systems have been developed as a proof of concept, and they have not been adopted for commercial use. Some acknowledged that system should be tailored to designer, field they are working in and type of communication used in it, for ease of use and maintenance (Hertz, 1992). Systems discussed in this section are referred to as CAD systems, but some include elements that are wider than only CAD is, and extend to other elements of CAED e.g. consideration of manufacturing, costing analysis, FMEA.

2.3.2. HCI for CAD

Whether CAD systems are taking a modelling or reasoning approach to conceptual product design, they require an interaction modality. The current standard, WIMP, is often seen as a limitation to CAD systems, hence different types of interfaces are being developed to control CAD software (input, modification, manipulation and visualisation of data). Interaction modalities can be classified based on two parameters:

- Specific actions performed in CAD systems and
- Technologies used to support implementation of these actions.

Five categories of specific actions performed in different systems were derived by Vuletic et al. (2018b), and include (ordered from less specific to more specific, with regards to key design activity performed using the interfaces):

- Manipulation – Rotation, translation, zooming; changing the viewpoint without actually changing the model.
- Modification - Changing the model e.g. subtraction, addition, change of shape.
- Virtual Sculpting/Surface Modification – Modification of shape but applied through surface modification, often emulating traditional sculpting.
- 3D Sketching – Sketching in the 3D environment. Either full 3D sketching or 2D sketching that is then used as a basis to extrude into a 3D shape, or a mix of both.
- Feature Modelling – Adding and subtracting features similar to traditional CAED systems.

Technologies used for interaction with CAED systems aiming to augment or replace WIMP are (ordered based on number of different supportive technologies required, in the ascending order):

- Touchscreens
- Haptic interfaces
- Pen input
- Brain computer interfaces

- Multimodal gesture based interfaces.

Multimodal interfaces combine a variety of different technologies in the same solution,"and can include gesture based interface detected using motion capture, gaze capture, haptic interface, tablet, mouse, pen, speech and virtual reality" (Vuletic et al., 2018b).

An illustration of different interaction modalities used for CAD interaction, categorised based on actions and technologies used is shown in Figure 2-1.

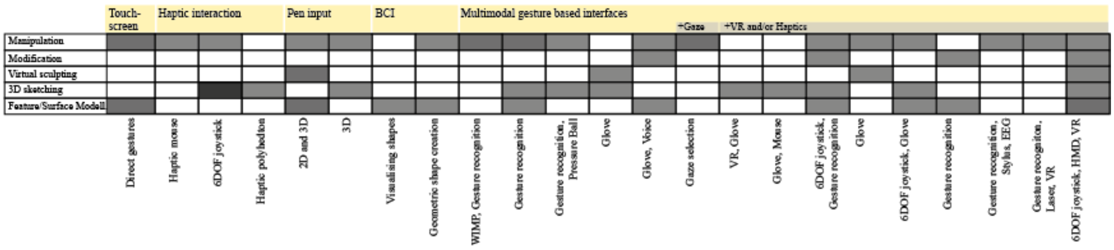


Figure 2-1 : Overview of HCIs, technologies enabling them and the activities they support

Motivation behind the idea to use different technologies for different applications is varied, and in the following sections, general findings for each of the technologies will be highlighted.

2.3.2.1. Touchscreen

Use of touchscreens is based on application of developed and accessible technology that is widely used in different fields to CAD systems. Direct rather than symbolic gestures for data input seem to be preferred in the research community (Radhakrishnan et al., 2013), and while the touch based input appears to be intuitive it can suffer from a lack of precision or finger occlusion of the screen (Kang et al., 2015). Consensus was that the optimal number of gestures and functions and type of gestures for touchscreens should be further researched (Radhakrishnan et al., 2013, Kang et al., 2015).

2.3.2.2. Haptic Interface

Haptics rely on applying tactile sensation and control in order to interact with computer applications, allowing users to feel contact force (Liu et al., 2005). Typically they are in a form of a 6DOF (6 degrees of freedom) joystick, but other types have been attempted such as haptic polyhedron (Ogawa et al., 2006) or 6DOF joystick with assigned virtual tools used for model deformation.

They allow designers to simulate clay modelling or foam modelling, sometimes called “virtual clay” (Sener et al., 2002, Evans, 2005), perform virtual assembly (Kyung et al., 2006), deform CAD surface models by pushing, pulling and dragging them (Liu et al., 2005), and require provision of minimal numerical detail about the design (Igwe et al., 2008). Historically designers have used clay for modelling and exploration of different concepts (Igwe et al., 2008), and that might mean that use of natural and intuitive tools such as haptics (IX et al., 2001) could improve working efficiency (Zhu, 2008) and creativity of CAD systems (Evans, 2005), and could potentially shorten the product development cycle (IX et al., 2001).

Haptics are most applicable to irregular shape creation, and are therefore often an add-on to existing interfaces (Liu et al., 2005). They are less suitable for fine surface definition and questions have been raised about their mainstream industrial applicability (Evans, 2005).

2.3.2.3. Pen input

Digital pen and a graphical tablet were generally used for sketching in 2D, 3D, 2D sketching on a 3D model (Shesh and Chen, 2004), or sketching shapes in 2D that are then recognised and computationally extruded into 3D solids (Alcaide-Marzal et al., 2013, Kim and Kim, 2006). Objects can then be manipulated and modified using feature modelling tools (Kim and Kim, 2006, Shesh and Chen, 2004). Some solutions provide support for unsteady, discontinuous and overlapping strokes that are often found in physical sketching but not in CAED systems (Shesh and Chen, 2004).

These types of systems have been found to be user friendly and quick to adopt (Kim and Kim, 2006) and showed promise for future use. They were all also in early stages of development. For example, the system developed by Shesh and Chen (2004) only supported drawing edges that were straight lines.

2.3.2.4. Brain-Computer Interfaces

Brain-Computer Interfaces (BCI) use EMG (Electromyography) and/or EEG (Electroencephalography) signals for design information input, either by feature modelling or imagining shapes (Vuletic et al., 2018b). The brain wave detection can be complimented with facial expressions detection for increased efficiency. It is a non-invasive approach as EMG and EEG activity can be recorded from the surface of the scalp/skin (Verma and Rai, 2013).

Study by Shankar and Rai (2014) reported on a solution where modelling began with a 2D sketch using line or arc tool. The position of the cursor was governed by head movements. Then the 2D sketch was extruded into a 3D part by thinking about “push” or “pull”. Other functions had relied on electrical activity resulting from muscular movements during generation of facial expressions (EMG) (Verma and Rai, 2013). Esfahani and Sundararajan (2012) trained a classifier to distinguish between primitive shapes (cube, sphere, cylinder, pyramid, or cone) imagined by a user, based on their associated EEG activity (Vuletic et al., 2018b).

Both systems required training and calibration sessions to recognise user specific EMG/EEG signals. While users have gotten used to the interfaces relatively quickly, and while it has been proven that individual participant performances were statistically similar (indicating BCI could become a generalised CAD modelling medium) (Verma and Rai, 2013), the users did experience fatigue (Shankar and Rai, 2014). For one of the solutions the average accuracy of shape recognition from EEG activity following training was 44.6% (significantly above chance level of 20% but still not high enough for industrial application) (Esfahani and Sundararajan, 2012).

2.3.2.5. Multimodal gesture based interfaces

The largest proportion of non-traditional interfaces explored in research was based on use of hand gestures. However, in some solutions they were further supported by various types of technologies for gesture recognition, or supplemented by other modalities.

Hand gestures are an expressive, natural and frequently used mode of human interaction (Tumkor et al. 2013). They are used to ensure intuitive systems that create 3D conceptual models quickly emulating interaction with physical world (Dave et al. 2013). Use of gestures would likely mean that levels of designer experience have less of an impact on their performance (Zhong et al. 2011).

Gesture based interfaces aim to provide a more intuitive interaction with a CAD system, but different researchers have taken different approaches and envisaged varying levels of integration with the existing CAD systems. Some developed systems for 3D model creation (Fuge et al., 2012), manipulation (Mine, 1997) and modification (Fuge et al., 2012, Weimer and Ganapathy, 1989) using feature and surface modelling. More recent solutions took the virtual clay approach, using one hand to rotate the object while the other held and squeezed a ball, which depending on the level of pressure created different sized ink dots creating 3D forms (Huang, 2007), or emulating the traditional clay modelling process in the virtual space (Dave et al., 2013). Others identified a series of gestures suitable for control of an existing CAD system (Rodriguez Esquivel et al., 2014, Tumkor et al., 2013), and found that fundamental changes in the user interface would be necessary for this to be successful (Tumkor et al., 2013). Zhong et al. (2011) propose the use of gesture input that is only used where it improves the design process, but can revert to the use of mouse and keyboard whenever needed.

Gestures were most frequently detected using motion capture, preferably using depth cameras which could support marker-less capture such as Microsoft Kinect (Tumkor et al., 2013), but in some cases gloves were used. Users often disliked the wearable devices (Lee et al., 2013), but in some cases they provided higher accuracy of detection (Weimer and Ganapathy, 1989, Fuge et al., 2012).

Gesture based interfaces were frequently supplemented with gaze capture as one of the input mechanisms. Gaze was used to select an object that an action would be performed on. Gaze was detected by remote cameras (Lee et al., 2013) or a customized head mounted type gaze tracker (Song et al., 2014). Gaze recognition was human centric and more intuitive than keyboard and the mouse, but time consuming to operate and in the case where mounted head set was worn it was not as comfortable. The remote cameras, which were not cumbersome, had some issues with different cornea recognition.

A more immersive design environment and process was attempted using the gesture and motion capture in the VR environment. In some cases, haptics were included, for example to allow a more realistic feeling of the shape for users during sculpting (Igwe et al., 2008). VR enabled faster and more natural approach to design creation (Ye et al., 2006). Some systems primarily focused on design, manipulation and modification in 3D CAD (Deering, 1996). Nevertheless, often VR systems focused on evaluation of a design with customers (Zhen-yu and Jian-rong, 2005, Naef and Payne, 2007, Kavakli et al., 2007). Collaborative design and evaluation in a VR environment or using virtual holography was also explored, in an attempt to achieve a more accessible and engaging experience (Bourdot et al., 2010, Noor and Aras, 2015). VR environments ranged from stereoscopic projection platform (Bourdot et al., 2010) to virtual environment viewed through 3D glasses or headsets (Varga et al., 2007, Zhen-yu and Jian-rong, 2005). Data input was sometimes supplemented by voice or wand, in addition to using hand gestures. Again, levels of integration with the existing CAD systems varied from discussing frameworks for future implementation (Igwe et al., 2008), to creation of strategies for commercial software integration (e.g. CATIA) (Bourdot et al., 2010), or actual implementation of a limited hand motion language in commercial modelling software (SolidWorks, SolidEdge and Autodesk) (Varga et al., 2007).

As most systems were in the early stages of development, and have not reached commercial application, a comparison with a WIMP interface has not been performed (Bourdot et al., 2010). Most studies tested the feasibility of the interface development, but did not account for the user experience (Fuge et al., 2012). Those that did test user perception found the new interfaces to be intuitive but have a learning curve (Dave et al., 2013, Bonnardel and Zenasni, 2010) and cause fatigue. Some researchers compared existing capabilities of VR systems using controllers for

3D sketching and sculpting with traditional 2D sketching for conceptual design, and found that while enjoyable they did not bring dramatic improvements (Lorusso et al.). Some found that participants with prior experience in CAD scored higher in satisfaction and operability, while all participants produced more original solutions (Varga et al., 2007).

Gestures used in the studies were prescribed, which simplified the technology implementation but reduced user satisfaction. Past studies have shown that humans are only able to store seven plus or minus two elements in their short-term memory (Miller, 1956). Some authors suggest that depending on the representation type it could be even less, three to five elements (Cowan, 2001), The number of commands in a CAED system is often higher than this, which may be a factor in user satisfaction when using prescribed gestures.

2.4. Summary

Initial CAD systems did not focus specifically on conceptual design; they instead saw design as an activity that could overall be improved by the use of computational support and 3D visualisation, including the conceptual design. However, over time it became clear that the nature of conceptual design, including rapid and frequent changes, and less than fully defined solutions aiming to convey a form and an idea rather than fully dimensioned details posed challenges that current approaches and technologies did not have a solution for. Computation techniques are not good at automating a process in which activities cannot always be predefined or predicted. Wealth of research is present in the literature exploring innovative CAD solutions tackling specific elements of conceptual design, but they have generally not been accepted by the product design industry or used habitually. Additionally, interfaces used for communication between the designer and the system have not been found suitable for conceptual design stage.

CAD systems have been found to enhance visualisation and communication, provide faster and more accurate solutions, accurately capture detailed design information, allow more time to be spent on ideas, support group creativity, improve perception of spatial features and relationships and support designers' problem finding behaviours. However, a mix of prescribed ways for interaction they employ and interfaces used to enable the interaction lead to substantial drawbacks. Specific activities can be more time consuming using CAD than pen and paper. Planning of steps required within CAD tools can lead to production of less creative outputs and pull the designer away from the design itself. It can lead to circumscribed thinking, premature fixation and bounded ideation, or make product evaluation difficult. In order to integrate the conceptual design within the CAD supported design workflow a need has been identified in the literature for improved interaction, possibly supported by new interfaces, and less regimented design approach better suited to the nature of conceptual design.

Gesture based interfaces or multimodal interfaces with gestures were identified in the literature as one of the possible modalities that may be able to introduce a more intuitive way of working. In the majority of the applications encountered, hand gestures were used, often in-air free form gestures, implemented using various technologies. They will be explored more systematically in Chapter 3 in order to assess their potential for use in conceptual CAED systems.

3. Touchless hand gesture interfaces

Chapter 2 provided an overview of the current capabilities, benefits, and drawbacks of CAD systems and their relationship with conceptual design. Current systems are constricted by and built around the capabilities of technology, not focusing on what is natural and intuitive to humans. Changing the mode of interaction with a computer system would be a step towards building a more natural and intuitive conceptual CAD system.

However, improvements to interaction interfaces could improve systems in many other fields, and in this chapter, an overview of gesture use in interaction interfaces in general is given, based on a results of systematic literature review[2]. Data from the review was updated in September 2020 to reflect the developments during the year the thesis was under revision. Particular focus was placed on exploration of gestures used for 3D design (3D object interaction, creation, modification and manipulation). At this point, the search was not limited to conceptual design only or a specific field,

[2] Vuletic, T., Duffy, A., Hay, L., McTeague, C., Campbell, G. and Grealy, M., 2019. Systematic literature review of hand gestures used in human computer interaction interfaces. *International Journal of Human-Computer Studies*, *129*, pp.74-94. https://doi.org/10.1016/j.ijhcs.2019.03.011

as approaches from related fields or wider design context may provide valuable insights.

The objective of this chapter is to explore the current state-of-the-art in gesture-based interfaces within it providing the overview of gesture use for applications focusing on design, in order to further explore the knowledge gap in the field.

3.1. Motivation for the review and the inclusion and exclusion criteria

Hands and hand gestures are a natural form and mode of human expression, interaction with the physical world and objects in it (Zimmerman et al., 1987, Buchmann et al., 2004). Gestures are used for communication and accompany speech in a range of forms, from simply following the rhythm of the speech, to conveying a specific meaning or a concept (McNeill, 1992, Quek, 2004).

They were widely explored as a form of natural and intuitive interaction for a variety of applications, sometimes including the use of arms or only focusing on fingers, in an attempt to reduce the complexity of interaction between humans and computers (New et al., 2003). Primary motivation for gesture use in an application has varied and some examples are: inclusion of inexperienced users and reduction of the need for training (Buchmann et al., 2004, Kim et al., 2005, Beyer and Meier, 2011); touchless operation guaranteeing sterility or safer interaction (Miller et al., 2020); immersion using Virtual Reality (VR) or Augmented Reality (AR) (Deller et al., 2006); expression of spatial concepts when externalising ideas (Vinayak et al., 2013); interactions with required functions without breaking visual contact with important elements of the activity e.g. controlling comfort functions in a car without taking the eyes off the road (Riener et al., 2013); or inclusion of an older population in everyday activities (Bhuiyan and Picking, 2011).

New applications are constantly being developed, supported by new technologies enabling better gesture detection and recognition. Expansion of the field of gesture based interfaces since 2013 has been facilitated by the development of sensors such as Kinect (Kinect, 2018) and LEAP (LEAP MOTION INC., 2018), enabling enhanced detection of gestures, portability and simpler implementation. Simpler implementation refers to the use of Software Development Kits (SDKs), which simplified hand detection and recognition by reducing the need for development of independent algorithms for every step in the process, and provided shared databases containing pre-programmed recognition of various hand poses.

In this chapter touchless hand gesture use for interfaces, which have reached the prototype stage, will be explored, in order to identify key research directions in the field of touchless gesture interfaces and then further explore its sub-fields focusing on design. The articles, 148 articles, were identified through a systematic literature review (Vuletic et al., 2019). Additional 10 articles were added to the review in the year this thesis was under revision. Research that has reached a prototype stage has been chosen, as it may contain evaluation of usability of gestures and deeper insight into how and why they were used. However, the main interest was in the nature and type of gestures used, and not the implementation details.

Existing work was identified providing an overview of the theoretical foundation of the gesture research often combined with speech. This theoretical foundation was used to describe and categorise the findings of the review. The theoretical foundation itself is given in Section 3.2. Patterns and commonalities between different approaches were explored, and if present, the reasoning behind the gesture elicitation choices was noted. This was done to aid the identification of key research directions in the field.

The nature of gestures was defined as a combination of the motions used and the role they serve in the interface. This was done as the same gesture may serve a different purpose in different fields, or could be chosen due to the ability of technology to capture it or recognise it. By combining the motion and the role of the gestures, a consolidated categorisation approach was achieved. Identified gestures were analysed in terms of their role in an interface, and classified based on the theoretical foundation identified from the field of gesture research. Section 3.2 will provide the conceptual framework and guide the interpretation of findings in this chapter.

Interfaces were included if they primarily explored touchless hand gestures, through experimental testing or prototype evaluation. Gestures aided with hand held devices such as wands or remotes were included if hands were required to participate in gesture formation, if users simply pointed a remote and pressed a button or wrote letters using a wand, solutions implementing those activities were not included. Full body gestures were excluded, but if arms or upper body were used along the hand gestures, they were included. Tablet, touch and pen applications were not included. Inclusion and exclusion criteria is summarised in Table 3-1.

Table 3-1 : Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Prototype built and tested	No prototype.
Interface primarily explore touchless gestures.	Gestures exclusively relying on touch e.g. tablet sketching using a pen or a finger excluded.
Gesture are primarily hand gestures, potentially aided with arms and upper body.	Full body gestures.
Wands or remotes included if they were required to participate in gesture formation i.e. performed role of a hand, for example pointing with a wand instead of the index finger.	Excluded if the only activity was pressing a button, writing letters using a wand.

3.2. Theoretical foundations of gesture research and gesture type definitions within different gesture classifications

This section provides a framework for the analysis of the gestures identified in the review of touchless hand gesture use in gesture interfaces. Gestures observed are hand gestures. Hand gestures, in the context of this thesis, are motions performed by a human's hand.

Hand gestures can be one or two handed, and include use of fingers, as long as fingers are not used exclusively. For example, if a pointing gesture is used to select an object that is then interacted with using the entire hand, then the pointing gesture is considered to be a hand gesture. But if a different number of fingers pointing up or different fingers touching each other are indicating a predefined action, and those are the only gestures considered in an interface then they are classified as finger gestures.

It used to be more difficult to track both hands due to a lower bandwidth or processing power of the devices used. However, modern technology enables seamless tracking regardless of the number of hands used, hence a distinction between one-handed and two-handed gestures was not made, unless it was important for the role of a gesture in an interface or fundamentally changed the type of the gesture observed. For example, if the posture of the left hand defined the operation that the designer wanted to perform, and right hand performed a dynamic action specifying parameters of it (Kang et al., 2013), the choice of handedness was made for a technical reason and was not further analysed. If a 3D object was manipulated with one hand, while the other hand was used to control the 3D scene (Bourdot et al., 2010), this potentially corresponded with the way handedness is used in reality, and would warrant further exploration.

3.2.1. Gesture symmetry

Observing how hand gestures are used for day-to-day activities, they can be classified as **unimanual** (e.g. brushing teeth or throwing darts), **bimanual symmetric** (e.g. lifting weights or rope skipping), or **bimanual asymmetric** (e.g. dealing cards or playing violin) (Guiard, 1987). Often two hands "cooperate", work in unison, to form a series of actions building on each previous one (Guiard, 1987), and temporal and spatial scales influence this cooperation. For example, while writing, a person holds a pen with one hand, holds, and occasionally adjusts the paper with the other. The hand holding the paper has a lower temporal frequency (changes happen less often), and a lower spatial frequency (paper does not move long distances) (Guiard, 1987).

3.2.2. Gesture temporality

Gesture temporality describes gestures in the function of how their form changes with time. Depending on their rate of change with time, gestures can be classified as static or dynamic. **Static gestures**, or postures (Vinayak et al., 2013), have the same form for the entire duration of the gesture, and if a "snapshot" or them was taken it would not change over time. **Dynamic gestures** change over time, and a hand moves through a sequence of positions to form a full gesture. McNeill (1992) identified three to five phases a dynamic gesture can have: preparation, prestrike hold (some gestures contain it, some do not), stroke, post stroke hold (some gestures contain it, some do not), and retraction.

3.2.3. Gesture context

Depending on the activity performed, and the goal gestures are aiming to achieve, gestures can be classified in different ways. In this thesis, this is defined as contextual classification. Depending on the context they are used in, in terms of the type of information exchanged, gestures can be classified as communicative or manipulative (Quek, 1995).

Communicative gestures convey information, and manipulative convey spatial position of objects or the ways they are manipulated. While this is also a mode of communication, it is specific to spatial information. Communicative gestures tend to be linked to speech. Gesture and speech are complementary communication features (Quek, 2004). Gestures supplement or substitute speech in order to convey meaning, complete a sentence or clarify ambiguous words (Kendon, 1985, pg. 215-234). Different authors focus on specific characteristics of gestures in the context of their use.

A summary of different types of contextual gesture classifications, derived by different researchers in the field, is given in Figure 3-1. Buxton (2018) (from Kendon (1988)) classifies gestures based on how similar their structure is to a language: gestures that form a **language of their own**, **emblems** with high link to language, **pantomimes** with medium link to language, gestures that were **language like** but had limited links to language, and **gesticulation** which has little to no link to language. Buxton (2018) also classifies gestures based on if they can be used independently from speech. **Independent communicative gestures** are those that serve a communicative purpose and are frequently used along with it, but convey a meaning even if detached from speech. **Speech related gestures** complement verbal communication, and do not possess an independent meaning. Cadoz (1994) classifies what is being communicated: **semiotic** gestures communicate meaningful information, **ergotic** gestures manipulate the physical world to create artifacts, and

epistemic gestures are used to learn from the environment through tactile or haptic exploration. Rimé and Schiaratura (1991) consider what the gestures refer to: **evocative object**, **object of speech** or an **ideation process**. These gestures, respectively, refer to the evocative object and elicit its presence in the common mental space between the speaker and the listener, depict the object spoken about, or closely follow the natural flow of speech and speakers thoughts during ideation depicting an abstract idea (Rimé and Schiaratura, 1991). Finally gestures can be **conscious**, **unconscious**, or combination of both, conditionally (Cassell, 1998). The term gesticulation was used earlier in this section to describe one of the levels of similarity of gesture structure to a language (Kendon, 1988). It is also used more generally, to designate gestures performed simultaneously with speech (McNeill, 2006).

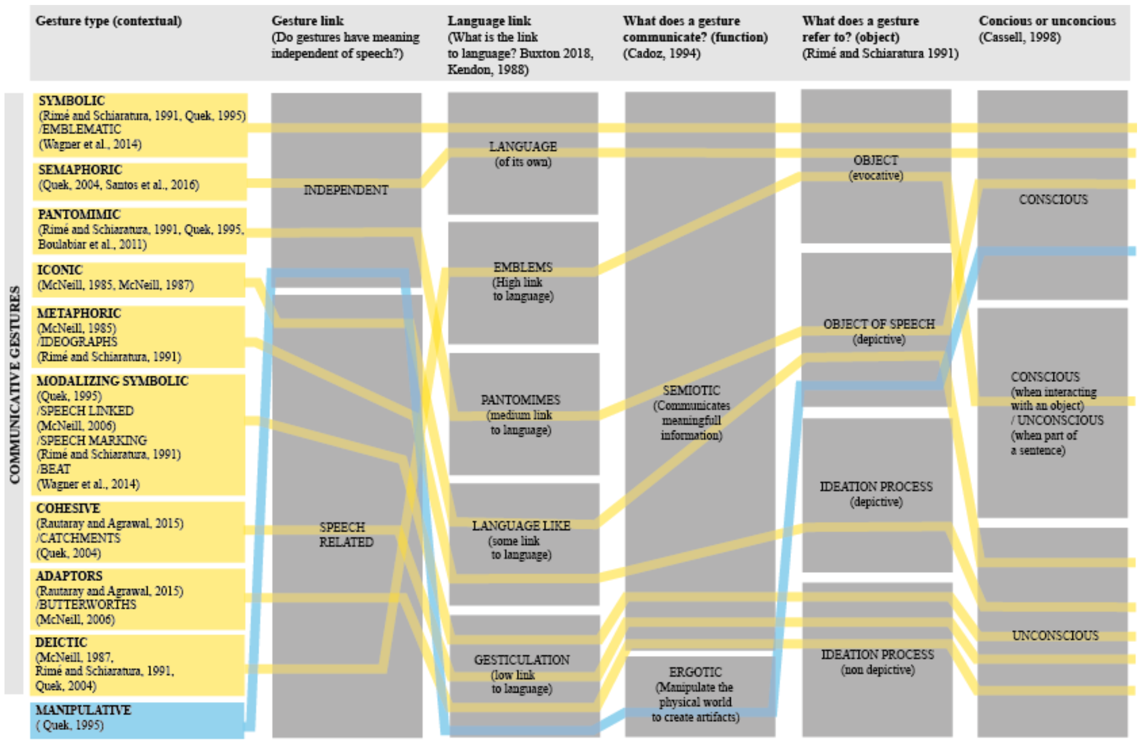


Figure 3-1 : Classification of gestures by context, adapted from Vuletic et al. (2019)

Contextual gesture type shown in the first column in **Figure 3-1** is the lowest level of decomposition of gestures in this classification, in terms of the context they are used in and the role they play in it. Where they generally fall under different higher-level classifications can be identified by following the connecting line in Figure 3-1. The connecting line emerges from each contextual gesture type category and crosses the sub-category specific gesture type falls under, across the columns to the right, for each subsequent higher-level classification. For example, symbolic gestures have a meaning independent of speech, are in a form of language, they are semiotic, refer to the object of speech and are conscious. Definitions of each contextual gesture type will be given in the following paragraph: symbolic gestures, semaphoric gestures, pantomimic gesture, iconic gestures, metaphoric gestures, modalizing symbolic gestures, cohesive gestures, adaptors, deictic gestures and manipulative gestures.

Symbolic gestures, alternatively called emblematic gestures (Wagner et al., 2014), represent a symbolic object or concept (Quek, 1995). They typically have a direct translation into words (Rimé and Schiaratura, 1991) and a widely accepted meaning (Wagner et al., 2014), sometimes specific to a group, class or culture. They do not have a morphological relation with what is being referred to (Rimé and Schiaratura, 1991). Some examples are “thumbs up” to indicate approval (Wagner et al., 2014), hand waving as a greeting (Rimé and Schiaratura, 1991) or “rubbing index finger and the thumb to refer to money” (Quek, 1995).

Semaphoric gestures are those predefined in a formalised dictionary used to trigger a predefined action. Often they communicate an intended symbol to a machine (Quek, 2004), and need to be learned before they can be used (Santos et al., 2016). Both symbolic and semaphoric gestures hold predefined meaning and refer to an object (are evocative). The difference is symbolic gestures assume common, shared understanding, whereas semaphoric gestures were developed for a specific purpose and only gain meaning once the user is trained to understand them.

Pantomimic gestures are imitated representations of familiar concepts that convey a narrative (Boulabiar et al., 2011) e.g. asking for a lighter by motioning usage of an imaginary lighter (Quek, 1995). Pantomime “plays the role of the referent” (Rimé and Schiaratura, 1991). Using the same lighter example, a speaker asking for a lighter interacts with the imaginary lighter shaping their hands as if they were using it.

Iconic gestures illustrate what is being said, the object discussed (Rime & Schiaratura, 1991), and their meaning is closely related to the semantic content of the speech (Holler and Beattie, 2003, McNeill, 1985). For example, a person talking about a globe rotating would perform a rotating motion with their hands. Rimé and Schiaratura (1991) further decompose the iconic gestures and split them into those describing a shape (Pictographs), those representing a spatial relation (Spatiographic), and those describing action of an object (Kinematographs).

Metaphoric gestures are similar to iconic gestures, but they represent abstract content (Wagner et al., 2014, McNeill, 1992), for example "dusting hands/palms off" to indicate something has been solved. They show a spatial representation of a speaker's thinking (Rimé and Schiaratura, 1991).

Modalizing symbolic gestures complement speech, providing additional information that was not contained in spoken content (Quek, 2004). Together they convey a different meaning. For example, a person asking "Have you seen that plate?" holding their hands far apart forming the shape of a plate to indicate it is large. The gesture adds a new element clarifying the statement and highlighting its underlying reasoning. These gestures compliment spoken statements (Boulabiar et al., 2011), and other authors call these speech-linked/framed gestures (McNeill, 2006), or speech marking gestures (Rimé and Schiaratura, 1991). Wagner et al. (2014) call them beat gestures, and focus on their temporal characteristics defining them as "fast movements of hand that synchronize with prosodic events, variations in pitch, loudness, tempo, and rhythm, of speech".

Cohesive gestures are thematically related to what is being spoken about, but are performed with a temporal distance. If a speaker was interrupted, once they continue talking about a specific theme the same gesture will reappear (Rautaray and Agrawal, 2015). In other sources, recurring gestures perceived to be related to recurring themes are called catchments (Quek, 2004, Yoshioka, 2005).

'Butterworth's' may or may not be a specific type of a gesture. They were believed to be gestures prompted by failures of speech e.g. "hand grasping while a speaker is trying to recall a word” (McNeill, 1992), but they were not successfully replicated in later studies (McNeill, 2006).

Adaptors are unconscious highly physical gestures used to release body tension such as tapping one’s foot quickly (Rautaray and Agrawal, 2015).

Deictic gestures are pointing gestures, used to indicate the direction of intended movement, or a direction of manipulation, with or without additional assigned meaning. Due to their directional nature, in some sources they are classified as a mix of manipulative and communicative gestures, or sometimes even considered limited manipulative gestures (Quek, 2004). They can point towards a realistically/visually or symbolically present object (Rimé and Schiaratura, 1991). They are one of the first gestures children start performing and some authors argue they might represent an abstract form of iconic gestures (McNeill, 1987).

Manipulative gesture classification is far less extensive, and gestures are generally considered **manipulative** if they interact with and/or modify a spatial component of an object in an interface (Vuletic et al., 2019). In a more limited fashion, they are described as gestures where “hand motion indicates a path or a placement” (Quek, 2004).

Thinking is believed to be image based, while speaking is believed to be syntactic (McNeill, 1987). If both are happening at the same time, which some researchers find occurs 90% of the time (McNeill, 2006), that may mean both types of thinking are engaged in simultaneously (McNeill, 1987). Some researchers believe that gestures are used in addition to speech to represent reasoning processes that could not be articulated (Church and Goldin-Meadow, 1986) or when the mental image cannot be easily translated into words (McNeill, 1987, Freedman, 1972). Kendon focuses on anthropology and origins of language, and believes rules of the language system govern what is spoken, and that spoken content has limited relation to any aspect of the structure that is being referred to (Kendon, 1986). Gestures that do not have rules to follow, i.e. those less linked to language, have more degrees of freedom of expression (Kendon, 1986). This may indicate that further research into ergotic and epistemic gestures, focusing on mental images independent from language formats is needed (Vuletic et al., 2019).

3.2.4. Gestures with or without instruction

If instructions for how gestures should be performed are predefined gestures then they are considered to be prescribed. If no instructions are present, they are free-form gestures, i.e. gestures that do not follow a predefined form.

Prescribed gestures are usually described by a dictionary of gestures defined prior to gesture use, the gestures need to be learned or trained, and the performance of a predefined gesture triggers a predefined action. How quickly gestures are adopted depends on the users' cognitive skills (Wachs et al., 2011), and risks exist that prescribed gestures may not fit with the users' preferences. They may also increase the users' cognitive load (Poupyrev et al., 2002, Shapir et al., 2007).

Free-form gestures are unrestricted and typically do not trigger specific uniform predefined actions (Vuletic et al., 2019). Free-form gestures are typically used to move objects in a virtual space, or form splines or surfaces in 3D modelling solutions. They are normally copied into the system the interfaces are used for i.e. paths traced by hand are recreated in the virtual space. As a result, they do not communicate symbolic or metaphoric meanings that prescribed gestures usually can convey. In their current form, although their name would suggest fewer restrictions, their application is limited.

3.3. Types of application and technology used

How hand gestures were used in specific interfaces was at times influenced by the purpose the associated application served, type of technology facilitating its implementation, and gesture capture, tracking and recognition approach supporting it (Vuletic et al., 2019).

Some gesture based interfaces were developed because they enable touchless interaction in a medical field (Lopes et al., 2017), reducing likelihood of contamination. Some allowed workers to input information while holding tools in their hands (Yamada et al., 2014). In either case, the application goals made one aspect of the gesture more important than anything else e.g. touchless interaction or ability to perform gestures while holding tools and this affected the choice of gestures implemented. Sometimes gestures themselves were not the priority, and they were elected to demonstrate the capabilities of Kinect or LEAP sensors, or to demonstrate a new recognition method. In other words, the motivation behind the use of gestures may thus affect how they were used, and before the gestures are analysed in more detail, an overview of application types and technology facilitating the implementation was conducted.

Often the gesture recognition approaches e.g. algorithms used for gesture recognition, were explored in the literature. As that type of research generally focuses on technical capabilities and computational development rather than the appropriateness of gestures for a specific application, they were considered to be out of the scope of this thesis.

This section provides an overview of the types of applications gestures were used in (including 3D modelling, assistive application, data input/authentication, manipulation/navigation, and touchless control), before covering the technologies used, specifically visual based, wearables and multi-modal approaches combining them.

3.3.1. Types of application

Gestures were first used in an interaction interface with a display in 1980 (Bolt, 1980). A prototype of a glove-based interface for 3D/VR object manipulation was the next step in gesture interface development, in 1987 (Zimmerman et al., 1987). More consistent development of gesture-based interfaces took place from 1993 to 2005, with one to three papers per year reporting on prototypes designed for robot control, Computer Aided Design (CAD), manipulation of 3D objects, navigation/selection in an application, or a variety of solutions with no specific application determined. Around 2006 an increase of interest in gesture-based interfaces is noticeable, with further substantial increase beyond 2011, likely due to the introduction of a variety of depth-based cameras.

Different applications, ordered chronologically and arranged in five key categories, **3D modelling**, **assistive application**, **data input/authentication,**

manipulation/navigation, and **touchless control** are shown in Figure 3-2. Each box represents the use of a specific application in one study, and the majority of articles report on a single application prototype. However, when the same set of gestures was tested using multiple technologies or for different applications, each technology or application was assigned a box. Numbers in the boxes indicate the type of specific technology used, listed in the legend.

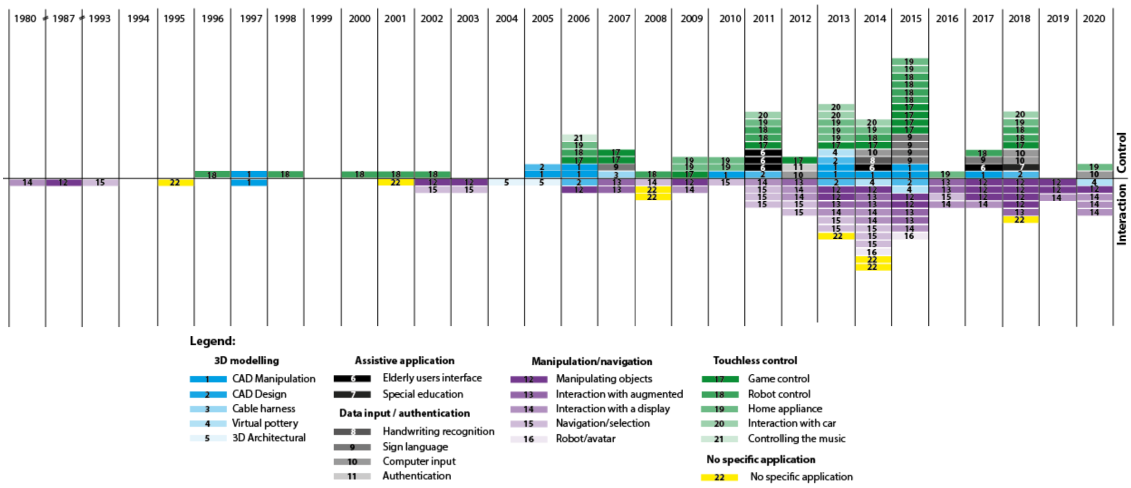


Figure 3-2 : Types of application for prototypes using gestures, adapted from (Vuletic et al., 2019)

The applications were categorised based on the immediate application, rather than the overall field of application. For example, if a system was used to allow a surgeon to consult 3D scans, rotate, zoom in, mark up, during surgery using touchless gestures to avoid contamination of hands, the application was classified as an interface for manipulation/navigation, rather than touchless control. Touchless interaction was a beneficial side effect for the medical field of application but the core nature of gestures used was manipulative. In an application providing remote control of a robot in a physically different location, the control is the core element, and those applications were classified accordingly as such.

3.3.1.1. 3D modelling

Shape creation was defined as the use of hand gestures to create a new shape in an empty space (Vinayak et al., 2013). Modification was defined as interaction with a shape in order to change its geometric characteristics (Vinayak et al., 2013). Manipulation was defined as an activity that changes its position in space, translates, rotates or scales it, but does not change its shape (Vinayak et al., 2013). In this thesis, CAD design encompasses shape creation, modification and manipulation. In some applications, only manipulation takes place, and this is classified as CAD manipulation. Applications were classified as 3D modelling applications if they interacted with spatial characteristics of 3D objects, usually creation, modification, and manipulation.

3D modelling applications were further classified as:

- 3D architectural urban planning (Buchmann et al., 2004, Yuan, 2005),
- Cable harness design (Robinson et al., 2007),
- CAD Design (Dani and Gadh, 1997, Kim et al., 2005, Qin et al., 2006, Holz and Wilson, 2011, Kang et al., 2013, Vinayak et al., 2013, Arroyave-Tobón et al., 2015, Huang et al., 2018),
- CAD Manipulation (Chu et al., 1997, Kela et al., 2006, Qin et al., 2006, Bourdot et al., 2010, Kang et al., 2013, Vinayak et al., 2013, Song et al., 2014, Beattie et al., 2015, Noor and Aras, 2015, Xiao and Peng, 2017), and
- Virtual Pottery (Dave et al., 2013, Han and Han, 2014, Vinayak and Ramani, 2015, Matsumaru and Morikawa, 2020).

All applications depended on 3D visualisation and the perception of 3D space, and often included interaction with the augmented or virtual world as a supporting technology. The majority used free-form gestures for the creation of splines or surfaces that built up a 3D model (Chu et al., 1997, Buchmann et al., 2004, Kim et al., 2005, Robinson et al., 2007, Holz and Wilson, 2011, Vinayak et al., 2013, Han and Han, 2014, Arroyave-Tobón et al., 2015, Vinayak and Ramani, 2015, Matsumaru and Morikawa, 2020). Simple prescribed gestures supplemented free-form gestures to trigger predefined activities e.g. pinch or grab to select an object.

3.3.1.2. Assistive application

Assistive applications aimed to provide a simpler interaction for elderly users with electronic devices, computers, or robots providing aid in assistive living environments (Bhuiyan and Picking, 2011, Nazemi et al., 2011, Zhu and Sheng, 2011, Rodrigues et al., 2014, Carreira et al., 2017). All articles reported on early applications that showed promise, and different applications used a wide variety of predefined semaphoric gestures. One application explored how gestures were used within special education for rehabilitation and learning (Ojeda-Castelo et al., 2018).

3.3.1.3. Data input/authentication

Prescribed gestures were used in applications to input information into a computer system. Gestures were defined by interface designers or users, and had to have been repeated accurately. Some applications were used for authentication only (Guerra-casanova et al., 2012), and others for computer data input (Cha and Maier, 2012, Yamada et al., 2014, Zeng et al., 2018). This input was sometimes based on handwriting recognition (Amma et al., 2014), or sign language (Adamo-Villani et al., 2007, Kapuscinski et al., 2015, Liu et al., 2015, Santos et al., 2015, Trigueiros et al., 2015, O'Connor et al., 2017, Lee et al., 2020b). For handwriting and sign language recognition, already established gestures were digitised.

3.3.1.4. Manipulation/navigation

Prescribed gestures were used to explore more intuitive interaction, manipulation and navigation modalities within different representation types.

Some applications were straightforward interaction with a display or a projection (Bolt, 1980, Choi et al., 2007, Foehrenbach et al., 2009, Beyer and Meier, 2011, Asadzadeh et al., 2012, Cauchard et al., 2012, Xie and Xu, 2013, Rossol et al., 2014, Saxen et al., 2014, Adeen et al., 2015, Wang et al., 2016, Braun et al., 2017, Osti et al., 2017, Dondi et al., 2018, Ma et al., 2018, Lee et al., 2020a, Lee et al., 2020c, Liu et al., 2020, Miller et al., 2020).

Interaction with augmented reality included a variety of technologies that enabled superimposed 3D representation of content and interaction with it (Reifinger et al., 2007, Lu et al., 2012, Bai et al., 2013, Hürst and van Wezel, 2013, Gangman and Yen, 2014, Adhikarla et al., 2015, Hernoux and Christmann, 2015, Shim et al., 2016, Saxen et al., 2014, Kim and Lee, 2016, Memo and Zanuttigh, 2018).

Applications used for manipulation of objects in VR or 3D environments that were not specifically developed for CAD, but for medical imagery or VR facilitated interaction devices, were classed as manipulative/navigational applications (Zimmerman et al., 1987, O'Hagan et al., 2002, New et al., 2003, Deller et al., 2006, Moustakas et al., 2009, Wright et al., 2011, Djukic et al., 2013, Jacob and Wachs, 2014, Kim and Park, 2014, Al-Sayegh and Makatsoris, 2015, Covarrubias et al., 2015, Lopes et al., 2017, Nicola et al., 2017, Park and Lee, 2018, Togootogtokh et al., 2018, Vosinakis and Koutsabasis, 2018, Kim et al., 2019, Yukang et al., 2019, Wilhelm et al., 2020).

Some applications did not include three-dimensionality or new technologies, but still explored gestural interaction used for navigation/selection (Baudel and Beaudouin-Lafon, 1993, Krum et al., 2002, Wilson and Oliver, 2003, Wachs et al., 2008, Pang et al., 2010, Ni et al., 2011, Reale et al., 2011, Lin et al., 2012, Ruppert et al., 2012, Colaço et al., 2013, Riduwan et al., 2013, Fuhrmann and Kaiser, 2014, Widmer et al., 2014, Lee et al., 2016).

Finally, interaction with robots or avatars that was not simply directing those using pointing gestures was classified as manipulation/navigation (Alvarez-Santos et al., 2014, Alves et al., 2015).

Nearly all gestures were predefined. They were either defined by interface designers, or preferred gestures were suggested/chosen in stages by users until a language of predefined gestures was built. Free-form gestures were used only for navigation through the space that was interacted with e.g. moving the mouse cursor, or moving an object that was virtually picked up. The majority of these interfaces were multimodal and gestures were used only in some modalities, hence had a limited breadth of application.

3.3.1.5. Touchless control

Gestures for touchless control were used to control entities without physical interaction. They allowed remote control or alternative, potentially safer, modes of interaction. These applications included:

- Controlling a music recording (Lee et al., 2006),

- Game control (Carbini et al., 2006, Bannach et al., 2007, Kratz et al., 2007, Xu et al., 2009, Chen et al., 2011, Roccetti et al., 2012, Sodhi et al., 2013, Dardas et al., 2014, Lv et al., 2015, Santos et al., 2015, Trigueiros et al., 2015, Yeo et al., 2015),
- Home appliance control (Kela et al., 2006, Liu et al., 2009, Schreiber et al., 2009, Chen et al., 2010, Pan et al., 2010, Boulabiar et al., 2011, Garzotto and Valoriani, 2013, Hoste and Signer, 2013, Takahashi et al., 2013, Dinh et al., 2014, Denkowski et al., 2015, Zaii et al., 2015, Wu et al., 2016, Wilhelm et al., 2020),
- Interaction with car controls (Mahr et al., 2011, Kajastila and Lokki, 2013, Riener et al., 2013, Lauber et al., 2014, Buddhikot et al., 2018, Zengeler et al., 2019),
- Robot control (Pook and Ballard, 1996, Savage-Carmona et al., 1998, Waldherr et al., 2000, Fong et al., 2001, Rogalla et al., 2002, Hasanuzzaman et al., 2006, Kim et al., 2008, Van Den Bergh et al., 2011, Xian et al., 2012, Gil et al., 2014, Boboc et al., 2015, Cicirelli et al., 2015, Marasovic et al., 2015, Xu et al., 2015, Kim et al., 2017).

Gestures used were a mix of predefined gestures triggering various predefined actions, depending on the application, and free-form gestures used for navigation. Applications for robot or game control typically used free-form gestures more. User preferences were occasionally considered during gesture elicitation for these applications too, most frequently for the home appliance control applications.

3.3.1.6. No specific application

Occasionally gesture interfaces were tested in a prototype without a specific application being assigned to it. These applications used prescribed gestures defined by the interface developers, and the application focus was primarily testing technology facilitating the interfaces or recognition approach (Quek, 1995, Rekimoto, 2001, He et al., 2008, Niezen and Hancke, 2008, Palacios et al., 2013, Huang et al., 2014, Zhou et al., 2014, Kim et al., 2015, Liu et al., 2018).

3.3.2. Technology used

Technologies facilitating gesture-based interfaces were based on a camera or sensor based tracking covering a certain range (visual based), or wearable devices such as gloves, rings, bracelets, bands with accelerometers etc. (physical based), which have inbuilt tracking devices. The former allowed the users to perform gestures using bare hands, whereas the latter required use of physical devices mounted or worn on the hands.

In Figure 3-3 the camera/sensor facilitated solutions are represented above the horizontal line, and wearable-facilitated solutions below the line. Each box represents the use of a specific technology in one study, and numbers in them serve to indicate the type of specific technology used, listed in the legend.

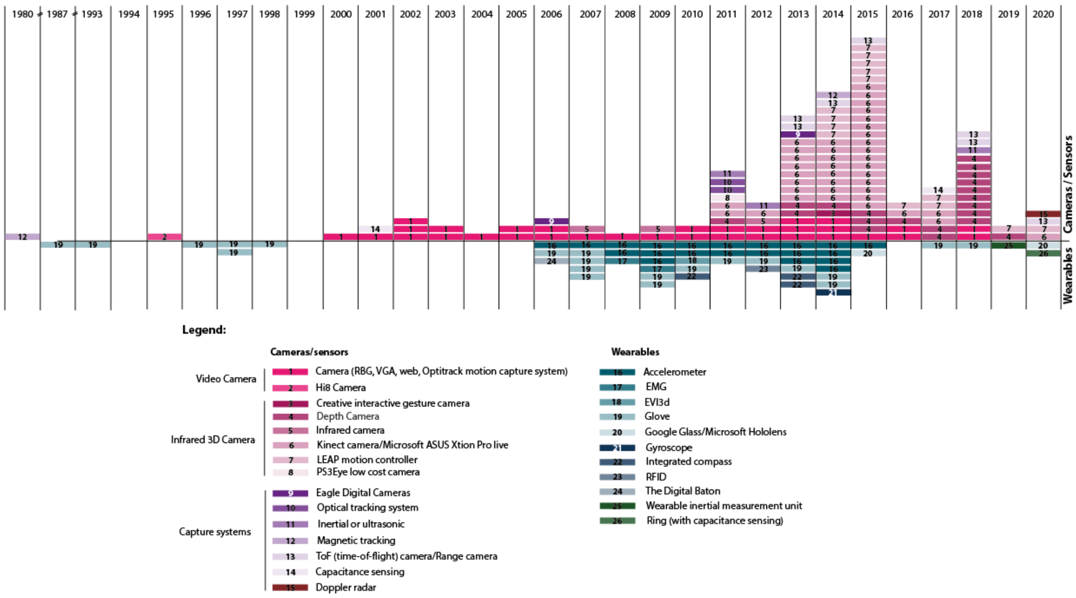


Figure 3-3 : Technology used to implement gesture interaction prototypes (Vuletic et al., 2019)

3.3.2.1. Visual based technologies

Visual based technologies fall under one of the three categories, from less to more complex technologies:

- Video cameras (video recorded than image recognition used to track gestures),
- Infrared/depth 3D cameras (based on infrared waves enabling depth perception e.g. creative interactive gesture camera, depth camera, infrared camera, Kinect

camera, Microsoft ASUS Xtion (ASUS Xtion, 2019), LEAP sensor and PS3Eye),

- Motion capture systems:
    - 3D optical motion capture systems,
    - Laser based tracking,
    - Magnetic based tracking, and
    - Capacitance sensing.

While visual based technologies have the advantage of not requiring wearable devices to be used, video cameras often necessitated use of markers placed on hands and fingers, to increase the accuracy of tracking. Infrared cameras, particularly Kinect and LEAP sensors were widely used in recent years, as 61 out of 158 studies (39%) use Kinect, LEAP or ASUS Xtion, and 69 out of 158 studies (43%), used some type of infrared camera. They are easy to transport, simple to use and do not encumber users, aligning well with the goal to achieve intuitive interface interaction. However, they still do not possess consistent precision and reliability required to provide sufficiently accurate gesture tracking, capture and analysis, e.g. LEAP is not sufficiently robust for use in medical clinical studies (Coton et al., 2016). Another drawback of cameras and sensors was occlusion (parts of gestures were hidden form the sensor by the hand in some positions). Finally, configuration was sometimes a complex and time-consuming process (Rautaray and Agrawal, 2015), and if it needed to be repeated frequently in use it might lead to low user satisfaction.

3.3.2.2. Wearables

Wearables included a variety of products that a user could wear, or were required to be held in a user’s hands. They included, ordered by technology complexity from less complex to more complex, gloves, accelerometers, markers, radio-frequency identification (RFID) based devices, compasses, gyroscopes, electromyogram (EMG) based devices, Google glasses, or bespoke solutions for gesture recognition such as EVI3d or The Digital Baton. A drawback of wearables was that shape, weight or limitations of the device could influence the performance of the gestures or lead to a higher degree of fatigue. Wearables can make users uncomfortable (Rautaray and Agrawal, 2015), detracting their attention away from the gestures. If other modalities were used with gestures facilitated by wearables, these limitations could have been propagated to them by influencing what they had to compensate for. Overall, wearables provide higher accuracy than visual based technologies, and they are easier to configure. The accelerometer was the most frequently used technology in 22 studies and as a supporting technology in an additional 17 (along with cameras, integrated compass or EMG).

3.3.2.3. Multimodal approach

Almost half of the articles reviewed (70 articles) used a multimodal approach, i.e. employed two or more different technologies. In some cases, this was done to balance the drawbacks of current technology, particularly accuracy or speed of tracking. However, occasionally different modalities were used as they provided a better fit for different communicative activities that complemented gestures. Supporting technologies were most frequently speech, Head Mounted Display (HMD) and VR. 3D modelling applications displayed a preference for camera/sensor solutions (15 out of 19 solutions were sensor based), particularly infrared cameras (9 out of 19 solutions). If wearables were used, the glove was the most frequently used technology, particularly if VR was used with it.

3.4. Types of gestures used

In this section, gestures observed in the reviewed articles were classified based on the definitions given in Section 3.2. The first classification was based on how well they fit the definition of a hand gesture. Then they were classified based on temporality and context, and levels of instruction guiding them, in Sections 3.4.1, 3.4.2, and 3.4.3 respectively.

Hand gestures, (as defined in Section 3.4.2) were observed in the 92% of the 158 articles. In nine articles authors discussed hand gestures, although the gestures were mostly finger, arm or upper body gestures Having said this, they were still included in further review, as the way they were used was very similar to the way hand gestures encountered were used and information gathered from the article was considered valuable. However, in Figure 3-4, which gives the overview of the types of gestures, used, they are classified as finger, arm or upper body gestures. The order of gestures was based on the size of gestures (magnitude of motion), from smallest to largest.

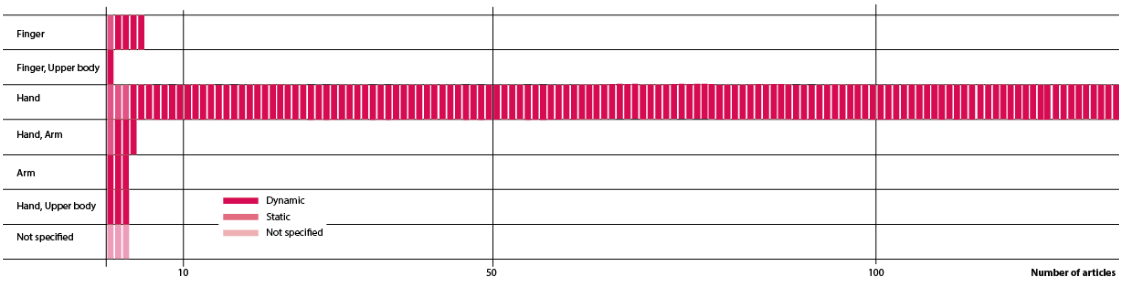


Figure 3-4 Finger, hand, arm and upper body gestures

Three articles were classified as “Not specified”, as the examples of gestures were not given and gestures were not described.

3.4.1. Static and dynamic gestures in interaction interfaces

The majority of interfaces used dynamic gestures (149 out of 158 articles – 94%). When static gestures were used in addition to dynamic gestures (in two articles), they were still classified as dynamic since the system required the capability to recognize both types of gestures. Only four interfaces used static gestures exclusively. Three interfaces did not explicitly state the type of gestures used, or provide sufficiently clear description of gestures based on which they could be categorised. Static and dynamic gestures are also represented in Figure 3-4, dynamic gestures using the darkest shade of pink, static gestures in the medium shade, and undefined gestures shaded with light grey.

3.4.2. Communicative or manipulative gestures

Different modalities of interaction were used along with gestures, and in multimodal applications speech and gestures were often combined (this was the case in 14 articles, 8% of the articles). In these cases, gestures were largely manipulative gestures. However, when gestures were used as the only mode of interaction (this was the case in 68 articles, 43% of the articles), it was more difficult to classify them as only communicative or only manipulative, as they do not always convey activity that could be readily interpreted to specific vocabulary. To overcome this, they were classified at a lower level of decomposition, by their contextual type of gestures.

Contextual classification of gestures encountered in interaction interfaces was based on the motions performed and the role gestures served in the application. After gestures were classified based on their contextual type (as one of communicative gestures or manipulative gestures), their link to speech, if it existed, and the form it was in was explored.

Only six of ten of the contextual sub-classes shown in Figure 3-1, were encountered in the reviewed articles: **deictic, free-form, manipulative, modalizing symbolic gestures, pantomimic and semaphoric gestures.** When gestures reached the application stage two gestures, while technically performing the same motion, can have different meanings and roles in the context they are used in, and hence were classified differently. For example, open hand, with the palm facing downwards, moving upwards while remaining parallel to the ground shown in Figure 3-5, can be used to translate a 3D model upwards in a virtual space or to turn a television screen on as a part of a home appliance control interface. In the first instance, it would be classified as a manipulative gesture, in the second as a semaphoric gesture. Therefore, additional rules used to code the gestures identified in the reviewed articles, depending on their role in the application, were defined as shown in Table 3-2.

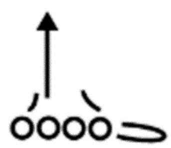


Figure 3-5 Gesture indicating both turning on a TV and translating a 3D model upwards

Ten articles did not report on gestures used in sufficient detail to determine the class of gestures. For example, it was clear that speech was used, but not specifically what for, what the utterances were and which action they were linked to (Bourdot et al., 2010, Alves et al., 2015).

Table 3-2 : Coding for contextual gesture types, reproduced from Vuletic et al (2019)

Activity performed with a hand	Aim/role	Classification
Ponting with one, two fingers or a fist.	To indicate direction, selection or location of a single point.	Deictic (Point to select).
	To continually move an object or indicate a path.	Deictic (Point to move).
No limitations, hand moves freely.	Reproduction of the motion in the system.	Free-form (Reproduction).
	Virtual hand emulates movement.	Free-form (Virtual hand).
Gestures vary, but are often one finger, two fingers of a full hand moving in a certain direction or tracing a circle.	To physically manipulate something in an interface e.g. translate it, rotate it, scale it, or trace an object shape.	Manipulative.
Rhythmic gesture.	Gesture where shape is not traced, but timing is.	Modalizing symbolic gestures/ Beat gestures
Gestures emulating interaction with a physical object e.g. pressing a button.	Same goal and role as with the emulated physical object e.g. button is pressed.	Pantomimic
Gesture is predefined, needs to be performed accurately and does not have to have any logical tie to the event it triggers.	To trigger a predefined event.	Semaphoric.

Gestures were first classified based on their role, and the context they were used in. Some interfaces use deictic, free-form, manipulative or semaphoric gestures exclusively. However, 43 of the applications (27% of the sample) combine more than one and up to four different types of gestures. In all cases instances of the same contextual classification type or combination of types were grouped together (using a Venn diagram) as shown in Figure 3-6, and then within the group they were placed close to the gestures used for the same type of application using the same type of technology, to further uncover patterns of their use. In total, eleven distinct combinations of contextual gesture types were identified, used across applications and supported by different technologies:

- Deictic
- Deictic and pantomimic
- Deictic and semaphoric
- Deictic, manipulative and pantomimic
- Deictic, manipulative, semaphoric and free-form
- Free-form
- Free-form and semaphoric
- Manipulative
- Manipulative and semaphoric
- Semaphoric
- Semaphoric and beat.

Figure 3-6 illustrates these groupings. Sections 3.4.2.1-3.4.2.4 provide further detail on all of the groupings and refer to the Figure 3-6. Definitions of all gesture types are given in Section 3.2.3. Further information on each individual application can be found in the Appendix A. Within each region gestures were additionally arranged based on the application they were used for (denoted with letters A to F to the left of the row of circles, as listed in the legend) and based on the technology facilitating them (denoted with numbers 1 to 4 above each of the circles). Where speech was used as one of the modalities, circles are filled and black.

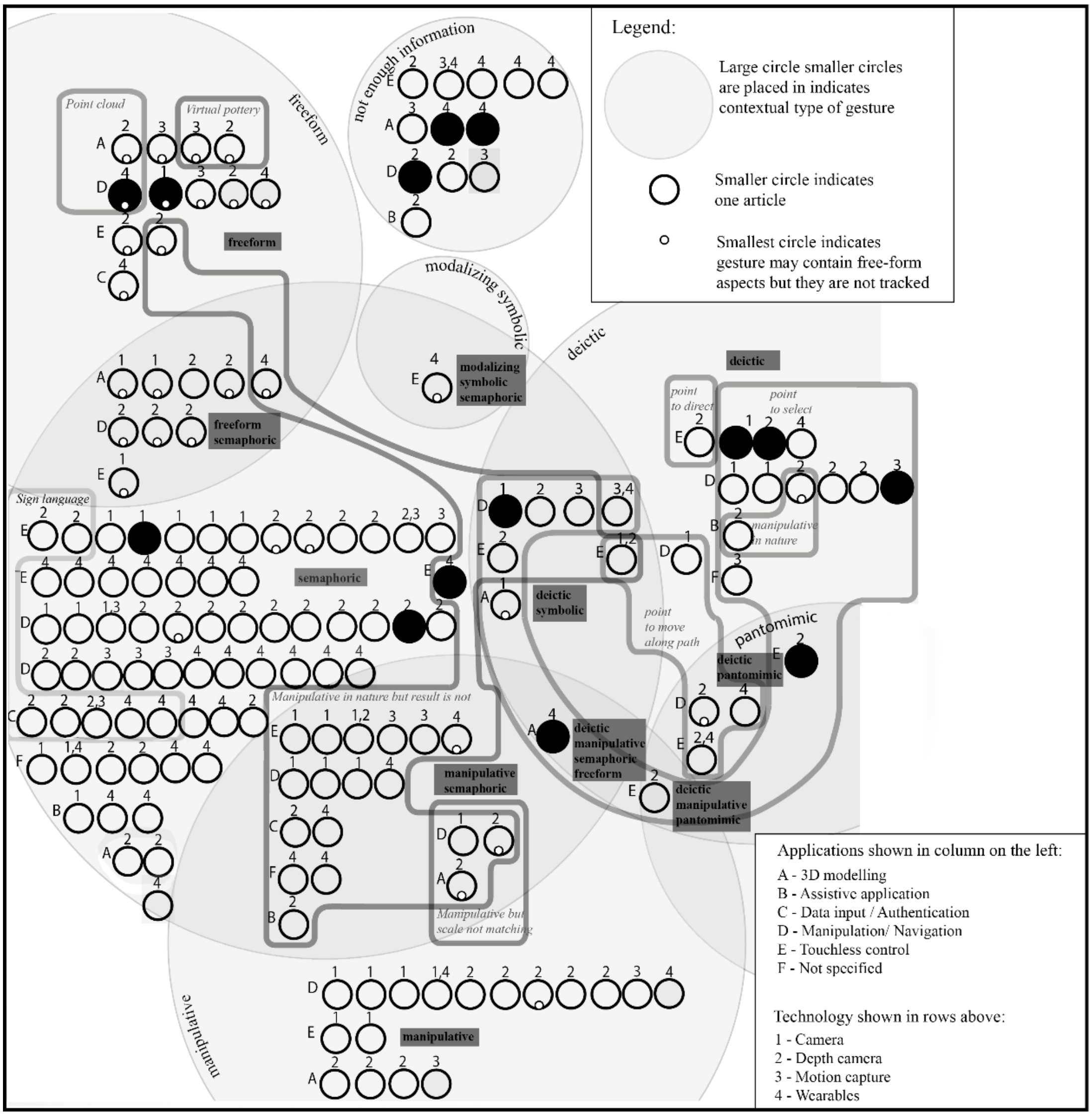


Figure 3-6 : Venn diagram of the contextual classification of gestures, their application role and the technology used

As the goal of the applications varied across the sample, applications were also grouped by the type of the activity the gestures were used for. In Figure 3-6 this is done by encompassing the applications in which the same type of activity was performed by a grey lined contour. The groups of activities more than one application was dedicated to were:

- creation of a point cloud,
- virtual pottery,
- sign language input, gestures pointing to direct an object,

- gesture pointing to select an object, gestures pointing to move an object along a path,
- manipulative gestures that performed a direct manipulative activity corresponding in scale and size to the object being manipulated,
- manipulative gestures that had the effect which was substantially different in scale e.g. a flick of a finger would move an object to the opposite end of the screen,
- and finally gestures that were manipulative in nature but where the effect was a symbolic activity assigned to a specific manipulative gesture, and it does not correspond to the form and path performed by the hand directly.

3.4.2.1. Deictic gestures and their combinations

Deictic gestures were pointing, using one or two fingers or a fist, to indicate direction or the selection of a point, or to continually move an object along a path created by moving the pointing hand. These three types of activities are grouped in Figure 3-6, (right hand side, middle) for all combinations of deictic gestures.

A combination of **deictic and pantomimic gestures**, was used for interaction with and manipulation of different representation types or for touchless control. Again, pointing was used for selection (in one application), and to move a cursor or an object (in the remaining three). Pantomimic gestures complemented the deictic gestures, and were used to swipe, pinch and grasp in order to pick up and pull and modify parts of objects. They were classified as pantomimic as they performed the same motion that could be imagined as an interaction for the similar activity/objectin the physical world. For example, to increase a hight of a cube shaped object, the edges of the top surface are grasped with a hand and pulled up.

Similar split of activities was performed using a combination of **deictic and semaphoric gestures,** with the difference that deictic gestures were pointing gestures used for selection only, and different predefined semaphoric gestures were used to trigger specific activities (sometimes manipulation of objects, but not exclusivelly).

A combination of **deictic, manipulative** and **pantomimic gestures** for touchless gaming (Sodhi et al., 2013). Deictic gesture was used to indicate where the character in the game is, manipulative gesture (swiping) was used to intercept a virtual button, and a pantomimic gesture (pushing) was used to push a virtual button.

A combination of **deictic, semaphoric, manipulative** and **free-form gestures** were used to manipulate 3D objects in the application developed by Chu et al. (1997). Deictic pointing was used to select or move/zoom, a number of semaphoric gestures to create 3D objects, and along with the free-form gestures to create surfaces and manipulative gestures to change the object dimensions.

3.4.2.2. Free-form gestures and their combinations

When used as a single mode of interaction **free-form gestures (**Figure 3-6, top left hand side) were completely unrestricted and either reproduced by the system tracking them, esentially copied in as a path or a surface, or emulated by a virtual hand created in a software system. Majority of applications using free-form gestures alone were used for 3D modelling or touchless control. Some 3D modelling applications created a point cloud as the hands move, subsequently recognised as a shape. Some were based on virtual sculpting, either using hands or virtual tools to modify a virtual shape on a virtual turntable. Where touchless control was the aim, free-form gestures were used to move virtual objects, windows or pointers, or to control a robot hand.

The same types of applications were also achieved using a combination of **free-form** and **semaphoric gestures**, where predefined semaphoric gestures were used to add different application specific functionalities by triggering predefined activities. In this combination of gestures, free-form gestures were completely unrestricted and generally used for selection or positioning of objects.

A number of non-free-form gestures contained elements of the free-form movement, but they were not the key element of the gesture, i.e. on their own free-form portions of the gesture would indicate a different activity , they were not fully tracked and were thus not classified as free-form gestures. In Figure 3-6 these were denoted with a smaller circle added to the bottom centre of the application circle.

3.4.2.3. Manipulative gestures and their combinations

Manipulative gestures (Figure 3-6, lower middle) were used for touchless interaction. They were used for translation, rotation, scaling/zooming, or object size manipulation, and the motion performed by the hand entirely corresponded to the goal of the activity e.g. to translate up, a hand would perform an upwards vertical motion. The form of the hand and exact motion was predefined for specific activities and specific applications, and had to be repeated in order for the gesture to be recognized. When the size of gestures or paths travelled by hand did not directly corespond to the achieved modification upon the object controlled, these manipulative gestures have a partially semaphoric nature, and in Figure 3-6 they are grouped as those that are “manipulative but scales are not matching”. For example to change all dimensions of an object proportionally (scale) the index finger and thumb were moved closer together, but while the hands move in the magnitude of a few milimeters, the object may be reduced by an order of magnitude more.

Combination of **manipulative** and **semaphoric gestures** were similarly largely used for touchless interaction, but the semaphoric gestures provided additional predefined functionality that could be triggered by performing a specific gesture.

Variety of other types of gestures contained elements that were manipulative in nature, and where a hand followed a path that resembled a manipulative activity, but their aim was not to manipulate and the action triggered was unrelated to manipulative activities. In Figure 3-6 these types of gestures are grouped together as “manipulative in nature but the result is not”. This is further discussed in the following paragraph, while describing semaphoric gestures which are manipulative in nature.

3.4.2.4. Semaphoric gestures and their combinations

Semaphoric gestures (Figure 3-6, middle left hand side) were used most frequently, and all aplication types had at least one article reporting on the use of semaphoric gestures. Here a user performs an abstract, predefined motion representing a concept using their hands that triggered an assigned predefined activity (Vuletic et al., 2019). To be recognized, the gestures needed to be learned and performed accurately. Semaphoric gestures were used on their own in 74 applications, but the specifics differed from application to application. The only exception to this were applications using existing languages such as sign language or hand writing recognition, in which 26 letters of the alphabet were used as symbols for recognition.

A subset of semaphoric gestures was where the **semaphoric gestures performed were manipulative in nature** but were used to trigger a predefined activity that was not. In some applications, all gestures used fell into this category, while in others a limited number of gestures had this characteristic. Within this type of gestures, the symbol performed by hands did not directly correlate with the activity, in meaning or nature. For example, while in manipulative applications moving a hand upwards would indicate translation of an object upwards, with semaphoric gestures it resulted in turning on a TV.

A combination of **modalizing symbolic** and **semaphoric gestures** was used in only one application (Lee et al., 2006) to control a music recording. Modalizing symbolic gesture is an auxilliary gesture that controls the speed of music played, by tracking its speed/beat. Two semaphoric gestures emulating a music conductor were used and recognised in addition to the beat gesture.

3.4.3. Prescribed and free-form gestures

Prescribed gestures, those defined prior to the use participants had to learn and perform accurately in order to interact with the system, were reported on in the majority of articles (141 articles, 89%).

Three home appliance control interfaces (Liu et al., 2009, Zaii et al., 2015, Wu et al., 2016) one 3D CAD application (Kela et al., 2006), and two applications exploring manipulation/navigation gestures (Liu et al., 2020, Yukang et al., 2019) initially allowed users to define their own gestures for particular activities. Then the most intuitive and most frequently used ones were selected and became the prescribed gestures. Others test gestures in stages, and reduce the number of proposed gestures based on different parameters. For example, Kim et al. (2008) used EMG to track predefined dynamic gestures for robot control, initially 20, that via testing were reduced to four that were easiest to perform and produced the highest quality of EMG signal. Both approaches were an advance towards considering preferences of the users, which could lead to higher adoption and acceptance of prescribed gestures. However, the problem remains that beyond the initial group of participants defining the gestures, they would still be prescribed. Future users of a system would not have been involved in the gesture elicitation, and would still have to learn the prescribed gestures. In Figure 3-7 depicting the breakdown of gestures based on the level of instruction, these gestures, were present in six systems, and were classified as conditionally free.

Free-form gestures were typically used to control an object e.g. direct a robot, create motion paths or surfaces, or modify virtual 3D object shapes or sculpt virtual clay. They were reported in 21 article, 13% of the sample. Free-form gestures were reproduced or copied into a system, and had a limited area of application, as symbolic activities still needed to be facilitated using a different type of gesture or different modality entirely.

Where authors did specify if the gestures were free or prescribed the authors' classification was accepted, but in four articles, gestures used were not specified and they could not have been classified.

In Figure 3-7 each box represents one type of gesture used in one prototype, and the colour of the box indicates the type of gestures used. If an article reported on more than one prototype, each prototype was assigned a box. Prescribed gestures are placed above the horizontal axis, and conditionally free, free-form and undefined gestures are represented below the horizontal axis.

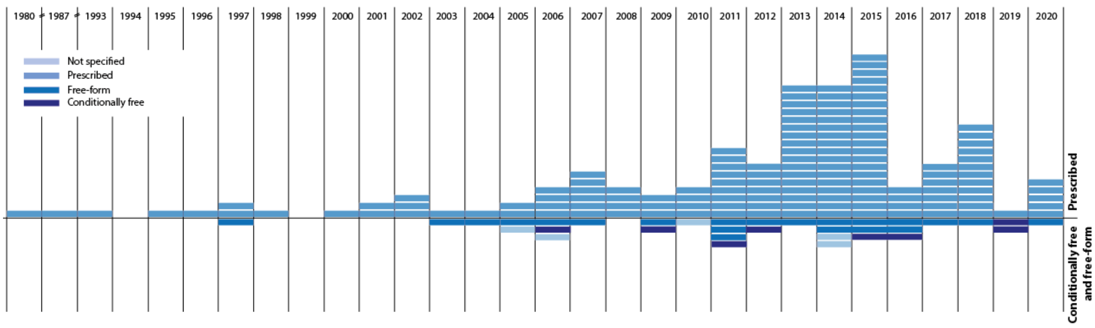


Figure 3-7 : Prescribed and conditionally free gestures

Current interaction interfaces primarily focus on prescribed gestures. Those that utilise free-form have limitations. It could be argued that fully free-form gestures would have the ability to convey a symbolic meaning in addition to the literal, copied shape, and would not have to be learnt prior to using a system (Vuletic et al., 2019). Meanwhile, user focused studies find that users prefer user elicited gestures, particularly those suggested by majority of the participants (Wobbrock et al., 2009), and find them more memorable (Nacenta et al., 2013). This indicates that further research into user generated and non-prescribed gestures is needed.

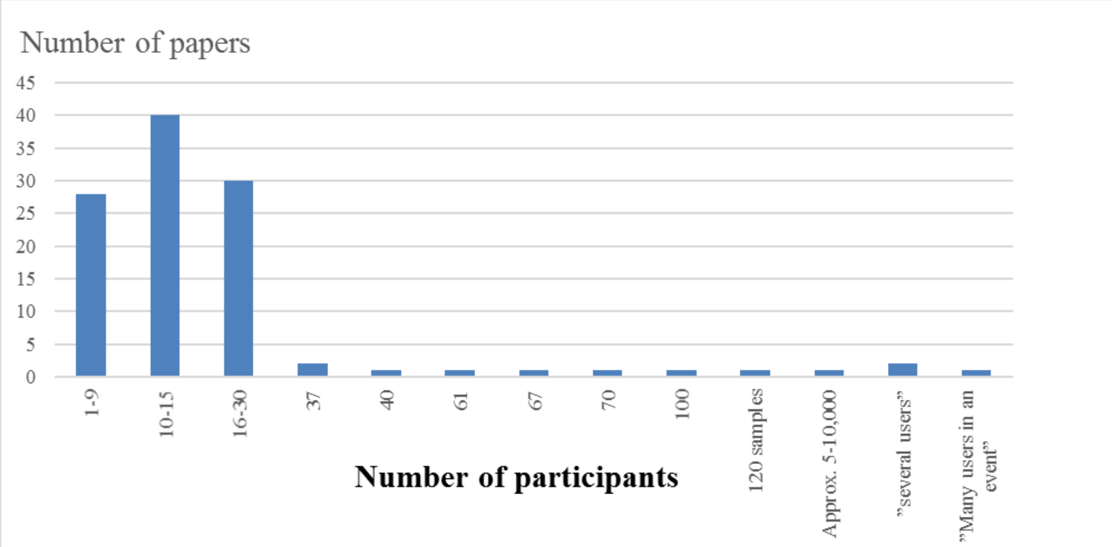
3.5. General findings on touchless hand gesture use

Typically, an article reporting on a gesture interface implementation has four main sections: 1. Reviews the literature on similar applications, 2. Reports on technology, gestures and conditions used, 3. Discussion of recognition methods, and 4. Reports the findings. If the articles did not provide one of these aspects, the study was not considered fully defined and repeatable. It was considered incomplete and lacking research rigour, but it was included in the review, as the findings were still valuable in understanding the field.

3.5.1. Number of participants and number of gestures

Gesture interfaces were tested or evaluated by users, but a large amount of articles (54 out of 158, 34%) do not report the number of participants included in the study. It should be noted that some articles tested slightly different versions of their systems in different studies, and in those cases, each study was viewed as a standalone interface. The number of participants for those that do report it is shown in Figure 3-8. In the majority of cases 10-15 participants took part (40 articles, 25%), 28 articles (18%) included less than 10 participants, 30 articles (19%) included 15-30 participants, one article had 32 participants, and two articles had 37 participants each (Vuletic et al., 2019).

Only four articles, 0.02% of the sample, included a substantially larger number of participants (40, 67, 70, and 100 participants). Three tested prescribed gestures. The first tested a control interface for a variety of household devices (Carreira et al., 2017). The second tested gestures performing holding a mobile phone (He et al., 2008). The third tested a TV control interface for elderly people, but gestures used in it were not specified (Bhuiyan and Picking, 2011). The fourth study with the largest number of participants required them to perform a single gesture that was assigned to "unlock phone" function, and then repeat it (Guerra-casanova et al., 2012). These articles did not classify or compare the gestures created by different participants, and while the larger number of participants was beneficial for the purposes of machine learning and gesture recognition mechanisms being developed, it was not influential in terms of observing the patterns of gesture elicitation (Vuletic et al., 2019).



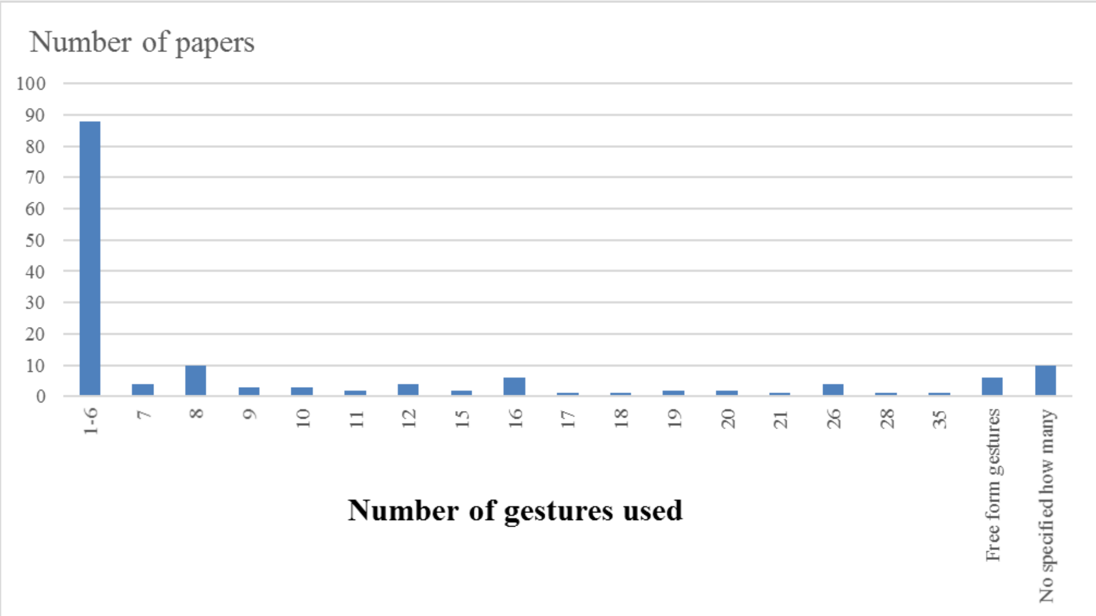


Figure 3-8 : Number of participants and gestures used identified in the sample, adapted from Vuletic et al (2019)

The majority of the interfaces tested six or less gestures (88 out of 158 reviewed articles, 56%). This may indicate that gestures were used for limited and specific forms of interaction (Vuletic et al., 2019). Six interfaces tested free-form gestures, which due to their nature had included an unlimited number of gestures. One article reports on a study that theoretically had an unlimited number of gestures, as they were suggested by participants for a number of predefined activities, and then the gestures participants found to be the most appropriate, were learnt by the system (Kim et al., 2017), which ultimately still limited their number. It is not clear how many variants for each gesture were learnt by the system, but the study only tested three gestures, moving the robot to the left, right or forward, as the onus was on the recognition methods and error detection.

3.6. Gestures for design

Observing the state-of-the art in the use of gestural interfaces for design, patterns have been identified. It should be noted that “design” in these applications typically covers 3D modelling (object creation, manipulation, and modification), as described in Section 1.1.

3.6.1. Patterns in the use of technology

Although there are no strict rules or clear prescription for the selection of the technologies used, from the gestures performed and the appllications they were used for, some patterns were identified.

Figure 3-9 visualises the relationship between type of gesture used in an application, technology used and the type of the application it was used in. It visualises the same content as the Figure 3-2 and Figure 3-3, but three-dimensional representation allows for representation of links between the type of gesture, technology used and the type of the application. As the focus of this thesis are gestures for design, the design focused applications are highlighted with a thick black border. In 70% of the cases (14 out of 20 articles), gesture based interfaces were supported by visual based technologies, likely due to the availability of affordable depth cameras and motion sensors. Deictic, manipulative, pantomimic gestures and their combinations, along with free-form gesture based 3D modelling, and combination of free-form and semaphoric gestures for 3D modelling were more often facilitated by the cameras, depth cameras and motion sensors. If wearables were used for these types of applications, they were typically gloves, and wearables were used when higher accuracy and ease of capture were required, usually when complex gestures were used.

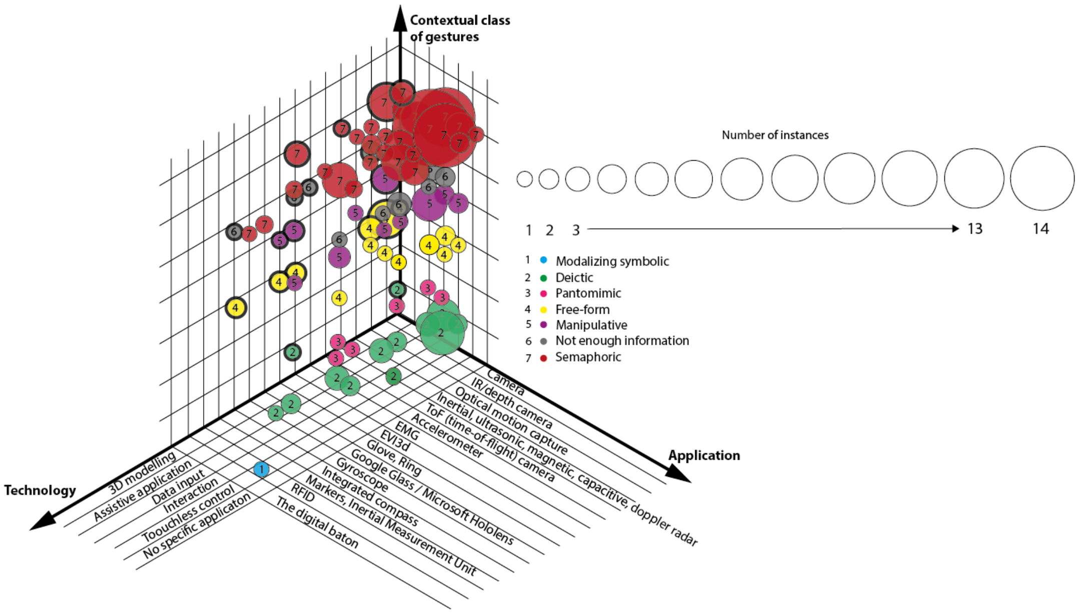


Figure 3-9 : Patterns in use of gesture types, technology and application types

Applications based on semaphoric gestures exclusivelly tended to use wearables more frequently than any other group of applications, but cameras and motion capture sensors were still more prominent even here. Out of 12 articles, 8 or 66.7% used visual based supporting technologies, and 4 or 33.3% used wearables).

Gestures used for interaction seemed to depend more on the technology used for the implementation than the needs of the system users. While neither were explicitly highlighted in the articles reviewed, the technology capabilities were considered in all of them, while gestures were elicited from the users of the system in only one article (Kela et al., 2006), and were then used to form a vocabulary of prescribed gestures.

3.6.2. How free are the free-form gestures?

Gestures with no limitations, where hands moved freely to input information or control the system in some way were dominant gestures used for 3D modelling applications. In some applications, shapes were created by drawing a profile that was then swept in space along a path, and further modified using free-form and parametric deformation and manipulation (Vinayak et al., 2013, Huang et al., 2018). Some applications used free-form gestures for surface creation, by tracing the motion of the hand and transforming that path into a new surface or spline (Kim et al., 2005, Qin et al., 2006, Holz and Wilson, 2011). Dani and Gadh (1997) developed a system where free-form gestures were used to create non-standard shapes, combination of predefined hand positions and voice commands were used to create standard shapes.

This supplementation of free form gestures with symbolic gestures or other modalities of interaction (speech or pressing a button) for activities which could not be performed appropriately by using of free-form gestures was common in 3D modelling and touchless control where 3D objects were manipulated in 3D, VR or AR environments. While unrestricted in terms of the shapes and paths that can be created in these types of systems, free-form gestures thus still have some limitations.

The alternative to this approach would be akin to what Kim et al. (2017) have explored, albeit not for 3D modelling, where they trained the system to learn gestures specific to different users for a number of predefined activities. This meant that the system was individualised for each user, and had a library of gestures to draw upon, although only for the chosen predefined activities. It could be argued that fully free-form gestures would have the ability to convey a symbolic meaning in addition to the literal, copied shape, and would not have to be learnt prior to using a system (Vuletic et al., 2019).

3.6.3. Relationship between gesture and speech

Interactive interface research is underpinned by theoretical foundations on gestures; however, it was largely based on gestures observed as speech aid, when gestures are used in parallel with verbal communication. Its classifications and definitions may not be aligned with the goals of free-form in-air gesture interaction or able to describe it fully. Additionally, even when speech is used in combination with gestures, it seemed the roles speech served were not always those described in the theoretical foundations (Section3.2.3). Speech was expected to complement the gestures semantically so that they could be classified as iconic, metaphoric, or modalizing symbolic gestures. Instead, speech often replaced what could otherwise be achieved by semaphoric gestures, seemingly to make technical application easier. This replacement took one of three forms:

1. Point and command approach - pointing gesture was used to indicate which object or direction is referred to, and then a one of a number of predefined utterances was used to interact with the object (Bolt, 1980, Carbini et al., 2006, Hoste and Signer, 2013, Choi et al., 2007, Chu et al., 1997, Wilson and Oliver, 2003, Moustakas et al., 2009, Pan et al., 2010, Dani and Gadh, 1997, Bourdot et al., 2010, Boboc et al., 2015). For example, a user pointed at an object, uttered "Move that", pointed at the second location, and uttered "There", in order to move an object. In 3D modelling/manipulation applications commands like 'select', 'dimension', 'scroll', 'detach', 'attach' were used. This approach was consistent with the role deictic gestures play in speech and gesture theory, but it was constrained to the use of predefined commands.
2. Replacement of gesture approach - speech was used to completely replace the gesture, not complement it (Rogalla et al., 2002, Dani and Gadh, 1997, Bourdot et al., 2010). An example for object manipulation is a command to 'create block, length 10 width 10 height 5', or provide verbal coordinates it should be moved to. Sometimes more natural speech could be used and the system could recognise the commands and map them onto predefined activities (Bourdot et al., 2010). This form of speech replacing gestures seemed to focus on convenience rather than the best fit for an activity.
3. Text input approach - words uttered were automatically recognised by the computer, and gestures were used to move words around to achieve the desired content or correct errors (Choi et al., 2007). Gestures and speech were completely separated, and there was no clear communicative or manipulative purpose in this approach. No 3D modelling applications used this approach.

This disparity between intended theoretical and applied use of speech and gestures might occur due to different goals two approaches have. However, whether the motivation behind application was the cause of the disparity, the gap between theoretical foundations and gesture application in interfaces remains. This may indicate that more research is needed to determine which gestures and gesture classes are the most appropriate for specific applications and technologies, particularly 3D modelling as it focuses on spatial characteristics of objects, which are hard to describe verbally. Such research could result in the provision of more structure for gesture elicitation process for interaction interfaces. As it is, interfaces supporting three-dimensional (3D) object manipulation exploring use of intuitive, affordable and non-intrusive interfaces are ubiquitous, but none of the approaches used have been established as the baseline for future development (Vinayak et al., 2013).

3.7. Summary

Gestures are a natural and intuitive form of human interaction often used to perform a communicative purpose. Gestures either supplement speech or describe an object or its position in space. They are one of the frequently attempted interaction modalities in various interfaces being developed, but they have not been explored, in depth, for design.

Overall, and in design applications, when symbolic concepts were conveyed gestures used were most frequently prescribed, and prescribed by the system designers. Prescribed gestures are adding to the users' cognitive load, which can be detrimental to the primary objective of the application. It has also been found that even when prescribed gestures were used, users often prefer user elicited gestures to those defined by system designers. When free-form gestures were used, they were imitation gestures i.e. hand motion performed was copied into the system exactly as performed, and were unable to support symbolic input. Although both were used in current gesture supported design system prototypes, neither prescribed nor free-form gestures with limited applicability were the most conducive for the development of natural and intuitive systems that can support the conceptual design process, without interrupting or encumbering it.

Design solutions were most frequently supported by sensing technology, as it had reached sufficient maturity and allowed reasonably accurate gesture detection while not requiring users to use additional equipment, which may be heavy or uncomfortable. Sensing technology is now well supported by prepopulated databases and algorithms simplifying gesture detection, and reducing the need for extensive programming. However, wearables were still used when higher precision is needed.

The way gestures were used in the interfaces in relation to speech, if speech was used as one of the modalities, was not always what would be expected based on the gesture theory. Where gestures would be expected to aid shape description for example, as that was the unique capability they can perform more accurately and more rapidly than speech, they were sometimes not utilised to their full potential. It is believed that this is often due to technical limitations, and this further confirms the finding from Chapter 2 that current solutions supporting conceptual design are often guided by what is easily achieved using latest technology developments, rather than what is needed to better support the nature of the design process.

The following chapter will further analyse the question of what the current approaches to supporting conceptual design are, and what the requirements of the conceptual design process are. It will also define the knowledge gap this thesis will be addressing.

4. Research challenge

This chapter will critically review the findings from the literature, reported in Chapters 2 for computational support for conceptual design and Chapter 3 for HCI, and identify the knowledge gap that will be addressed in this thesis. Then the research problem will be defined. The criterion the outcomes of this chapter will be based on is the disparity between the nature of design and systems supporting it. Limitations of existing research will be discussed; research problem identified and the approaches that will be taken in this thesis in order to address the research problem will be discussed. Finally, the study objectives and tasks will be defined.

4.1. Limitations of existing research

In developing computational systems to support conceptual design, two streams are dominating the research. One is focusing on CAD systems for conceptual design in terms of design process/models, aiming to align capabilities of the systems with the nature and activities of conceptual design in order to support it better, and the other is aiming to supplement this with improved interaction modalities that do not interrupt and disrupt the design process, but instead enhance it.

However, the outcomes of this research are not yet fully accepted by the design industry, due to a variety of reasons. Solutions exploring design process and aiming to improve CAD system processes to fit it better are generally either focusing on visualisation, using sketching in 2D, 3D or a mix of both. Nevertheless, in most cases these solutions do not diverge significantly from current CAD systems, and do not provide sufficient computational support for development of frequently evolving and often vague and unfinished concepts.

There are improvements and interesting developments allowing for some level of flexibility in design, but none of the solutions have yet reached the levels of maturity or usability to warrant industrial application. Solutions focusing on functional mapping, knowledge support, emergence and data capture introduce novel and pertinent elements to better support conceptual design, increase creativity and allow evolving designs to be appropriately captured in the system. However, each of the systems reviewed only supported limited aspects of the conceptual design process, and again, the majority have not reached large-scale implementation.

Solutions exploring interaction modalities aiming to improve the interfaces used for CAD systems do not focus on the design process directly. Instead, they aim to create interfaces that are intuitive and natural enough so that users are able to express their ideas faster, easier and without interrupting their thinking processes, and thus indirectly contribute to the improvement of computationally supported conceptual design systems. These approaches however focus on technology rather than designer needs, and alignment with the conceptual design process and its requirements. Need for supporting the design process is stated, but not implemented.

Gestures have been identified as one of the most prevalent modes of interaction used in newly developed interfaces for CAD systems. In order to explore how gestures have been used in other contexts that have a spatial element of interaction, a wider review of in-air 3D gesture interaction systems has been completed. While the goals of the systems were slightly different, some similarities were found in all of them, including the interaction systems developed for design and CAD applications. While gestures were used extensively as an intuitive and natural modality of interaction with applications, they were typically defined by the researchers, and not elicited from the envisaged users. Specific gestures used were often chosen because they were similar to activities preformed in current interaction interfaces or because they were easily recognisable using technology currently available to the researchers (Schmidt, 2015). Identification of intuitive and natural gestures was frequently the underlying aim, but the inclusion of technology in the elicitation process diverted the focus towards ease of implementation. Even during application evaluation, focus was most frequently on the evaluation of the application or its usability, and not the gestures or if they were appropriate for the chosen activities. Only one design-based application initially elicited gestures from the users, and based the prescription on these (Kela et al., 2006). It also stated that personalisation of gestures was preferred.

4.2. Research problem elements

Requirements identified from the literature review on CAD and conceptual design (Chapter 2) and state-of-the-art in gesture use in interfaces (Chapter 3) indicate that it is necessary to meet the need for:

- Ability to generate and manipulate ideas quickly, represent vague and changing designs (continual evolvement) (Müller et al., 2003, Shesh and Chen, 2004, Company et al., 2009, Alcaide-Marzal et al., 2013).
- An interface incorporating natural human actions and utilising intuitive modes of interaction (Oh et al., 2006, Ye et al., 2006, Fiorentino et al., 2010, Verma and Rai, 2013, Rodriguez Esquivel et al., 2014, Shankar and Rai, 2014).
- Less focus on process of the interface use and more on design (requirements of the product) (Ye et al., 2006, Robertson and Radcliffe, 2009, Fiorentino et al., 2010, Huang et al., 2019).
- Minimal to no training (Buchmann et al., 2004, Kim et al., 2005, Beyer and Meier, 2011).
- Improved user experience (incorporating user sourced requirements earlier in the interface development process) (Wobbrock et al., 2009, Nacenta et al., 2013).
- Integration with the product lifecycle (seamlessly transfer the model created to detailed design and beyond) (Brunetti and Golob, 2000, Horváth, 2000, Company et al., 2009, Krish, 2011).
- Representation means that are in harmony with the speed of ideation (Dickinson et al. 2005; Horváth 2000) allowing the design to be visualised as it is being carried out (Vidal and Mulet 2006).
- Improved perception of spatial features (Vinayak et al., 2013), and
- Reduced cognitive load (Huang, 2007).

In summary, to ensure that future interaction between a designer and a system supporting the conceptual design stage of a product design provides required functionality; such system should support the requirements of the conceptual design process listed above and include its envisaged users in the elicitation of gestures for the interface. To explore this, this thesis aims to answer the question of "What gestures would designers use naturally and intuitively if they were not constricted by technology and the design process imposed on them by CAD architecture?" In order to answer it a gesture vocabulary of user-elicited gestures for design will be developed, as a first step towards achieving a more natural and intuitive interaction with a system supporting conceptual design. The details of the scope of this work are defined in Chapter 1.

4.3. The approach to addressing the research problem

In this section, approach to addressing the research problem will be introduced, in terms of gesture elicitation, data analysis approach, number of participants involved and the process used to evaluate the findings.

4.3.1. Gesture elicitation

As mentioned in Chapter 3, gesture based interfaces tend to include gestures chosen by the researchers developing them, often due to ease of application or alignment with the technology used. Only one of the studies reviewed in Chapter 3 has attempted this without linking the gestures to technology used to detect them (Jahani and Kavakli, 2018), however the reported findings were high level and applications seemed to diverge from design into car comfort control interfaces. Other applications that have reached the prototype stage in the design field did not elicit gestures. To explore what the most suitable gestures for design activities are, a well-defined gesture elicitation process is needed. It appears that a framework guiding the gesture elicitation for practical application does not yet exist, not on the higher level, in terms of which aspects of interfaces would be best supported by gestures, nor for design specifically, in terms of how to select the most appropriate gestures for specific activities (Vuletic et al., 2018a). The need for studies identifying the most appropriate hand gestures for design interfaces is identified in the literature (Huang et al., 2018).

Moving away from the practical application, user-based gesture elicitation has been explored in the field of HCI. Specifically looking at in-air user based gesture elicitation, user sourced gestures have been explored for AR environments (Piumsomboon et al., 2013), TV control (Dong et al., 2015, Dim et al., 2016), and recently design related interfaces such as descriptive mid-air interactions (Jahani and Kavakli, 2018) and 3D CAD modelling in conceptual design (Khan and Tunçer, 2019). There have been no studies exploring conceptual design in isolation from the technology that may be used to support it, and this is the gap addressed in this thesis. User based gesture elicitation approach followed in the majority of the studies listed originates in work by Wobbrock et al. (2009) and Morris et al. (2010), focusing on exploring the most appropriate gestures for surface technology interaction e.g. iPad. The approach is usually slightly modified to better match the needs of what is being explored and technology facilitating it. The core of this approach will be adopted in this thesis, although it will be adapted for the needs of conceptual design. Chapter 5, Section 5.1 will provide descriptions of the existing approach and the changes introduced to it.

4.3.2. Analysis

Discussions regarding what is considered statistically meaningful and how reliable, justifiable, generalizable and repeatable results can be achieved are present within design science (Cash, 2018). Questions have also been raised regarding how meaningful the quantitative approaches used in user based gesture elicitation studies are, such as agreement rate definition for example (Tsandilas, 2018). Agreement rate is one of the only metrics consistently used in the field of user elicited gestures (Vatavu and Wobbrock, 2015), and it will be used in this thesis. However, it will be supplemented by metrics measuring significance of findings such as Fleiss κ, as suggested by Tsandilas (2018). In order to remove subjectivity from the gesture elimination process during sample analysis, Chi square, a metric establishing likelihood of an event occurring by chance, will be used. This is further discussed in Chapter 6, Section 6.3.

4.3.3. Number of participants and their background

Studies focusing on user-generated gestures typically have small sample sizes, which range between 10 and 20 participants. Some studies found that users generated more diverse gestures than gesture researchers (Wobbrock et al., 2009), and that gestures initially suggested by a larger number of users scored higher during the evaluation (Morris et al., 2010). Both of these studies focused on 2D tablet interaction, not 3D in-air gestures, but they imply that the inclusion of a large number of participants during gesture elicitation might be beneficial.

There were instances of studies using a substantially higher number of participants e.g. 100 participants were included in the study by Guerra-casanova et al. (2012), however the participants performed one gesture each that did not convey any specific meaning. More detail on these can be seen in Section 3.5.1. In the studies with substantially higher number of participants the key aspect was recognizing each individual gesture, and not assessing which gestures would be the most appropriate for the nature of the activity or building a vocabulary of gestures for a specific activity.

Finally, there were applications where participants could use gestures freely, and the system was learning gestures for a specific user and specific predefined activities (Kim et al., 2017). However, this specific application was not in a design field. It focused on improving gesture-based robot control during human-robot interaction, without extensive training but instead focusing on error rates. Work performed in this thesis aims to contribute to a similar future development in the field of conceptual design. Determining the required participant numbers in a study to reach the saturation depends on a number of factors such as quality of data, the scope of the study, the nature of the topic, the amount of useful information obtained from each participant, methods and the study design used (Morse, 2000).

Prescribed recommendations are not readily available for most fields. Usability studies identify 3-20 participants as typically valid for problem discovery, and 8-25 for comparative studies (Macefield, 2009). Typically, for qualitative studies data would be collected until saturation is reached, and for a quantitative study, an a priory power calculation would be performed in order to establish a required number of participants (Faul et al., 2007, Faul et al., 2009). However, for this calculation it is necessary to have a pre-defined number of samples. In this study, qualitative data was to be collected in the post study questionnaire, but the gestures would be quantitatively analysed. Since participants will be suggesting their own gestures, without any limitations imposed, it will not possible to establish how many different gestures they would propose. This is why the decision was made to stop data collection when no new significant developments were identified with the increase of participant numbers i.e. when a participant does not suggest any new gestures.

Studies focusing on gesture elicitation of in-air gestures typically include participants belonging to the general public, not specialists in a specific field (Wobbrock et al., 2009, Khan and Tunçer, 2019). This is done intentionally, so that elicited gestures are not influenced by prior experience, and are more easily generalizable for the wider audiences (Wobbrock et al., 2009). However, the studies performed in this way typically elicit gestures aimed at a specific technology e.g. surface pads. They focus on relatively simple activities, do not require creation of complex shapes and will be used by the general public e.g. TV control. Gesture elicitation performed for conceptual design is not linked to any specific technology, and could result in creation of a highly complex shape. It also needs to comply with requirements of the field discussed in Section 4.2, which may not be intrinsic to the general public. Hence, the decision was made to elicit gestures from designers, and evaluate these gestures using non-designer participants, to improve likelihood of generalisability. Details about participants and their background are given in Chapter 5, Section 5.3.3.

4.3.4. Evaluation process

Research focusing on in-air gestures for AR/VR applications in some cases combined gesture elicitation and evaluation i.e. the same participants suggested and evaluated gestures (Piumsomboon et al., 2013). In other studies, 20-40 participants were involved in gesture elicitation, but gestures were then evaluated by an order of magnitude smaller number of experts e.g. 41 participant in the study by Khan and Tunçer (2019), but then evaluated by four experts.

Studies performed to test gesture-based prototypes often did not follow an in-depth evaluation process to determine the appropriateness of the gestures for the specific application, or their efficiency, as their primary objective was to test the efficiency of the application itself.

In this thesis, in the gesture elicitation phase study participants will only suggest gestures. This group will consist of product design students and designers, and more detail on the participants will be given in Section 5.3.3. Then the resulting gesture vocabulary will be evaluated by a different group of participants. The evaluation participants will be non-designers in order to reduce the bias designers may have introduced and evaluate how appropriate the elicited gestures are for those without design training. The aim is for the resulting, refined, vocabulary of gestures for design to be more suitable for the use by non-designers.

4.4. Study objectives and tasks

In order to address the research problem defined in Section 4.2, three objectives and a number of tasks for a gesture study were defined:

Study objective 1 (SO1). Identify the key elements of a gesture vocabulary for form creation . i.e. What would the gesture vocabulary for form creation look like and can it be defined using user based gesture elicitation?

- Task 1.1. Identify gestures participants perform in response to the referent for creation, manipulation and modification of a number of 3D objects.
- Task 1.2 Analyse the identified gestures to achieve statistically meaningful, reliable, justifiable and repeatable results.
- Task 1.3 Establish a user defined set of gestures, a vocabulary, which aims to serve as a starting point for future conceptual design interface development.

Study objective 2 (SO2). Establish if the form of the objects interacted with affects the gestures performed to test study robustness. i.e. Do shape and recognisability of objects that are interacted with significantly affect the gestures performed?

- Task 2.1 Observe if the form of an object affect the type of interaction.
- Task 2.2 Observe level of agreement between participants’ perceptions of their own activities and the actual activities performed.

Study objective 3 (SO3). Explore the object creation workflow when participants are not confined by the procedural rules of a CAD system. i.e. Are established procedural rules used in CAD systems appropriate for gesture supported conceptual design?

- Task 3.1 Compare the activity sequence between guided and free object creation.
- Task 3.2 Provide recommendations for the improvement of procedural rules for the conceptual design stage.

4.5. Summary

Literature review reported in Chapters 2 and 3 has resulted in the identification of a number of limitations present in the existing research. CAD systems aiming to support conceptual design have not been accepted by the industry in the field of product design, primarily due to low maturity. They also support elements but not the entire conceptual design process. There are inconsistencies between the nature of the conceptual design and the functionalities of the computational systems and unsuitable interfaces that disrupt the designers' process and focus on technology rather than designers' needs. Further exploration of interfaces for in-air gestures developed in fields focusing on spatial interaction identified the need for elicitation of gestures appropriate for the requirements of the activity being performed, rather than those focusing on ease of implementation or defined by the researchers developing the system.

Combined, these limitations contributed to the formulation of the knowledge gap, which is that it is not known what gestures designers would use, without instruction and without limitations imposed by the technology currently facilitating, or being able to facilitate the conceptual design, and the design process imposed on them by CAD architecture. To address this gap, the research problem is to develop a vocabulary of in-air hand gestures for conceptual design that is isolated from current technology and elicited from designers. Research methodology developed to address this knowledge gap is presented in Chapter 5.

5. Research methodology

Following the research problem definition and general approach to addressing it in Chapter 4, it was necessary to define how it will be addressed in detail. This chapter defines the methodology that will be followed in the study performed to identify the vocabulary of hand gestures for conceptual design.

A user centred study was chosen, designed to identify natural and intuitive gestures for conceptual design. The key goal of the study was to discover how designers would perform conceptual design if technology was not limiting them and if they could use their hands to create, modify and manipulate virtual objects in any manner they wished to. The intention was to identify designers' intuitive and natural response to the design problem at task, separating them from consideration of what is currently achievable by available technology. Gestures performed will be identified, parsed, coded, categorised and analysed for patterns and relations. The outcomes would then form a gesture vocabulary for form creation. The process of research design development, testing via pilot studies and refinement resulting from them is detailed in this chapter. Parts of this chapter are to be published in the paper accepted with major changes and currently under revision by the publisher[3]. The outcome of

[3] Vuletic, T, Duffy, A, Hay, L, McTeague, C, Campbell, G & Grealy, M, 'A novel user-based gesture vocabulary for conceptual design', *International Journal of Human Computer Studies – accepted for publication with major changes. Currently in the revision process.*

this chapter is a fully defined research methodology that was followed in the study, and its outcomes are reported in Chapter 6.

5.1. Elements adopted from established user based studies

Elements of established methodologies from the literature exploring user-defined gestures were adopted. One goal of the established user based methodologies was to ensure the separation from available technology. Researchers in the field achieve this by portraying an effect of the gesture in some manner and asking participants to perform the cause of this effect i.e. gesture causing it (Wobbrock et al., 2009, Piumsomboon et al., 2013). This approach was first developed by Wobbrock et al. (2005) during the study aiming to maximise the guessability of symbolic input, and this is why it is sometimes referred to as “guessability study methodology”. It was later expanded to be applied to general gesture elicitation from users. Wobbrock et al. (2009) also disassociate the technology and the system they are eventually aiming to build from the interaction. They do this by following the “Wizard of Oz” approach where the response to a participant’s action is emulated by study designer to confirm to the participant that their activities are implemented and acceptable (Lee and Billinghurst, 2008).

The study reported in this thesis takes the same approach. However, it does not provide any feedback from a system; instead, it instructs the participants that any action they can imagine is possible and achievable, and that there would be no technical or recognition difficulties. They were told they are in a “magical room” that would know what their gestures mean. In linguistic terms, the effect of a gesture is a referent, as the gesture performed refers to it (McNeill, 1992).

The study was recorded using video cameras. It was envisaged the full study would consist of two parts. Part 1 in which participants responded to a number of predefined activities, and had a limited time to perform the activities in any way they saw fit. The aim of Part 1 was to identify most frequently suggested gestures for some of the common manipulation and modification activities. Part 2 aimed to observe flow of a conceptual design activity, allow participants to use activities and gestures they found appropriate to achieve a proposed design. Part 2 did not have any time limitations. Both parts of the study were tested and refined through their respective pilot studies (results of Pilot study 1 have been published in Design2019 conference[4]). The pilot studies are reported in the Appendix B. In the second part of the study, where users' thought process was important, think-aloud protocol was included.

After the participants completed both parts of the full study they were asked to fill in a questionnaire providing further information on their perception of activities performed during the study. The questionnaire was designed by the author, and is available in the Appendix G, Section G1. Typically, elicitation studies pose two questions post study, using Likert scale for the answers. For example, how good of a match for purpose and how easy to perform a gesture was (Wobbrock et al., 2009, Piumsomboon et al., 2013), or how easy the task was and how well were participants able to convey their intentions (Khan and Tunçer, 2019). Original questionnaire was designed in part to collect further information about the appropriateness of the study approach, and in part, because the goal was to evaluate the gestures by a different group of participants during the evaluation stage instead of having participants evaluate them during the study. Since participants, aside from time limitations, had no other limitations imposed or instructions given on how to perform the gestures, it was assumed they performed gestures they found appropriate and easy to perform. However, participants were asked to report any struggles with the activities in the last question of the questionnaire.

5.2. Differences from established user based studies

Studies in the field typically use non-experienced or non-technical participants, with regards to technology being used, as they are believed to behave differently to designers and system builders (Wobbrock et al., 2009) and to avoid influence of previous experience (Piumsomboon et al., 2013).

In the study reported in this thesis, a decision was made to use design students (Product Design Engineering PDE, at University of Strathclyde), in their 3rd, 4th or

[4] Vuletic, T, Duffy, A, Hay, L, McTeague, C, Campbell, G, Choo, PL & Grealy, M 2018, 'Natural and intuitive gesture interaction for 3D object manipulation in conceptual design' Paper presented at 15th International Design Conference, Dubrovnik, Croatia, 21/05/18 - 24/05/18, .

5th year of studies. At this level, students are considered to have a sufficient grasp of design, have used CAD in their projects, but are considered to still have not fully adopted the traditional way of working.

CAD knowledge can be classified as declarative “knowledge what”, procedural “knowledge how” or strategic “metacognitive knowledge” (Chester, 2007, Hartman, 2009). Declarative knowledge is knowledge of commands in CAD and these are particular to a specific CAD system (Hartman, 2009, Diwakaran and Johnson, 2012). Procedural knowledge is knowledge of tools and processes that are not linked to a specific CAD system (Hartman, 2009). In practice, this knowledge is manifested in knowledge of possible alternate methods to create a CAD model, and helps the experts perform better (Diwakaran and Johnson, 2012). Strategic knowledge includes knowledge of geometry creation and manipulation enriched with knowledge about the design considerations inherent to the model creation process, software processes, and past experiences (Hartman, 2009). Experts in CAD are those that possess strategic and not only command or procedural knowledge (Bhavnani et al., 1993). The efficiency of the design process relies on the task decomposition strategies (Bhavnani and John, 1997). Experts are faster problem solvers than novices, as they are able to put a problem in the specific context of a particular domain and use the tools strategically (Hartman, 2009). Experts are able to anticipate the need for changes and build models in ways that allow feature reuse if the changes are later needed (Diwakaran and Johnson, 2012). Experienced designers focus on the requirements (Robertson et al., 2007, Robertson and Radcliffe, 2009) and solution-focused strategies (Lawson, 2005), are less likely to be affected by circumscribed thinking, but might show mild levels of bounded ideation (Robertson et al., 2007, Robertson and Radcliffe, 2009). Novices tend to focus on problem-focused strategies (Lawson, 2005).

3rd- 5th year students were considered to have good declarative and procedural knowledge of CAD, and medium strategic knowledge. They have typically not spent extensive amount of time working in professional design environments, but they have spent at least three years of working on student projects or limited projects with industry. They were not expected to suffer from bounded ideation i.e. would not focus on CAD tools and how to use them rather than ideation. They were also considered less likely to suffer from circumscribed thinking i.e. limit their design steps to those possible in the CAD software they were familiar with, as their knowledge of both CAD tools and design processes was at an intermediate level. They have all successfully completed design projects requiring intermediate level use of CAD in their first three years of studies, i.e. they are highly skilled in use of frequently used CAD commands but may still need guidance in using more advanced tools such as surfacing for example. They can be considered advanced beginners or novice designers that have key characteristics of designers (Liikkanen and Perttula, 2009).

Use of participants from the general public with no design or CAD experience was considered, however finally decided against. While the element of novice view and approach to the problems would be beneficial, participants were required to have good perception of space, and members of general public were less likely to consistently possess this ability. This could have been overcome using a space and 3D perception test as a qualifier for the inclusion of the study. However, the additional problem was that conceptual design problems are niche and require a level of creativity and imagined manipulation of vague concepts that the general public potentially would not possess, and would be much harder to test for. PDE students have displayed the spatial perceptions skills, creativity and concept manipulation throughout their training.

As discussed in the beginning of this section, typically user-based studies use non-technical and non-experienced participants, concerning technology being used, in order to remove the effects of known technology limitations. However, they typically do use the technology intended for use in the application during the gesture elicitation process in some manner even if the effects of the gestures need to be emulated using the “Wizard of OZ approach”. While this research was inspired by more widely available new technology allowing recognition of 3D in-air hand gestures, the VR/AR technology or sensing equipment was not used in the gesture elicitation part of the study. This choice was made in order to avoid limitations introduced by the system used to represent 3D objects and types of interactions possible in the system.

Therefore, a choice was made to use a 2D screen to display the 3D objects users are asked to interact with, and evaluate if the users imagined the objects shown as 3D in the Pilot Study 1. Initially, the recording of gestures was done using a video camera and a LEAP sensor, in order to explore if the infrared capture had reached the sufficient levels of accuracy to be used. The additional benefit of this choice would be that screens are present in most workplaces and if the results had shown that 2D screen approach was appropriate for gesture identification that would mean similar studies designed to identify natural and intuitive gestures for 3D object interaction could be ran without extensive investment in the portable or additional equipment. The Pilot Study 1 also tested the ability of participants to respond to the activities shown to them, without being given specific instructions guiding them. In the Pilot Study 1 the activities were discrete, and did not provide information on how participants progressed from one gesture to the other. The Pilot Study 2 tested an approach that would allow users to propose the activities they wished to use to create an object, and in the second stage propose their own sequence of these activities entirely. Pilot studies have shown that this approach was appropriate as the objects were perceived as 3D and participants were able to complete the activities without difficulties.

The setup of the pilot studies and their findings are reported in the Appendix B. The research approach followed in the full study is detailed in Section 5.3.

5.3. Research approach

The full study sequence is illustrated in Figure 5-1. The full study consisted of two parts. Part 1 was tested in Pilot Study 1, and Part 2 was tested in Pilot Study 2. Both pilot studies demonstrated that participants were able to follow the steps required of them, and confirmed that in general, the study set up was suitable. The full study draws upon these, and has introduced required changes identified from the pilot studies to the initial study design.

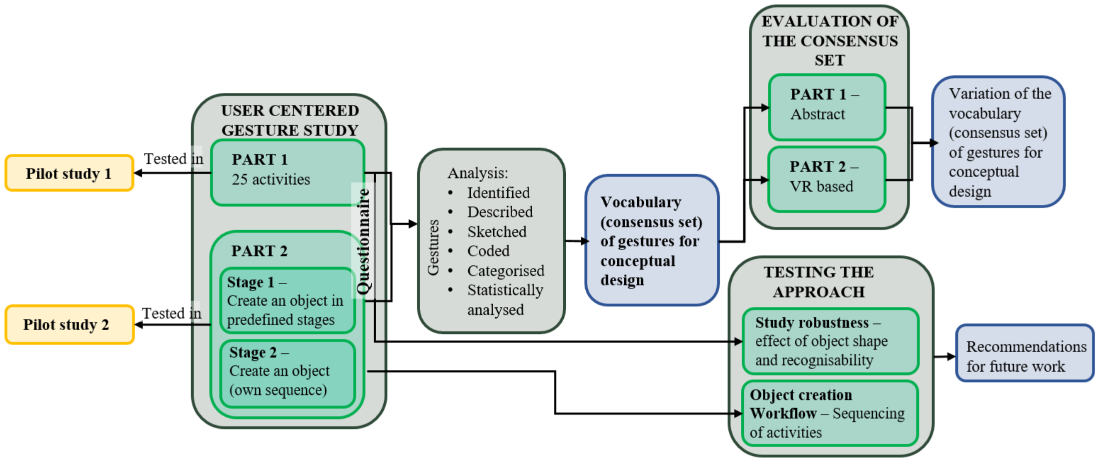


Figure 5-1 Illustration of the full study

To ensure participants are not learning how to perform the activities in Part 1, and adopting what they learned in the Part 2, one half of participants performed Part 1 first, and the second half performed the Part 2 first. Detail descriptions of both parts of the study are given in Sections 5.3.1, 5.3.2 and 5.3.3. List of participants and the order they performed the two parts of the study is available in the Appendix G, Section G.1. All participant information has been anonymised, and no participants from the pilot study took part in the full study. Following the analysis of data, described in detail in Section 5.3.4, the outcome of the full study is the vocabulary (consensus set) of gestures for conceptual design. The vocabulary (consensus set) was then evaluated through an evaluation study, described in Section 5.3.5. Then the consensus set was evaluated using a two-part evaluation, abstract and VR based, described in detail in Section 5.3.5. The outcome of the evaluation of the consensus set is a variation of the vocabulary (consensus set) taking into account a non-designer perspective and some application limitations. Then the study approach was tested by testing the study robustness, described in Section5.3.6, and through observation of the object creation workflow, described in Section 5.3.7. The outcomes of these are recommendations for future work.

5.3.1. Study setup

In Part 1 the participants were asked to observe an animation of a 3D rendered part being manipulated or modified (3D part being manipulated or modified is referred to as an activity), and then use their hands to perform the gesture they believe would result in this activity i.e. imagine they were causing the activity. A flowchart illustrating this process is shown in Figure 5-2.

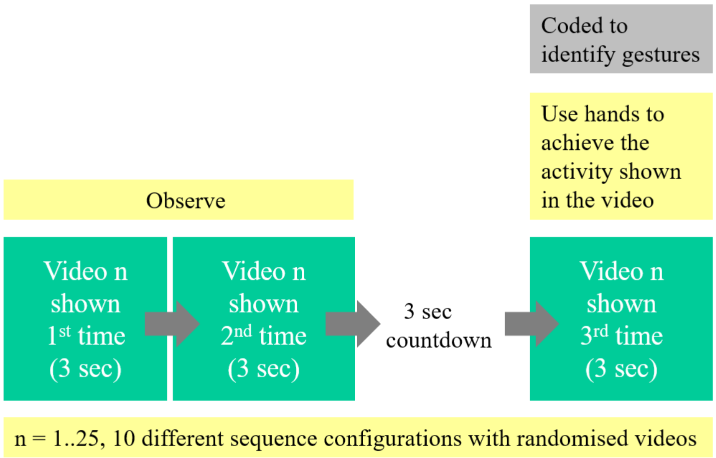


Figure 5-2 : Sequence of activities in Part 1

25 activities were shown to the participants, and these are shown in Figure 5-3. Each activity was shown to the participants three times. The first two times they saw an activity they were asked to observe it only, and the activity was shown twice to ensure the participants register it fully (the number of repetitions was tested in the pilot study). When they see it for the third time, they were instructed to imagine they were causing it using their hands, and perform gestures they believe would result in the activity they see as it happens. Each activity lasted three seconds. This was done to identify the participants' instinctive reaction rather than allow them to think about what they would do in CAD for example. It was hypothesised that a short time interval to perform a known activity would allow the recording of their natural reactions rather than creation of analogies with the way the same activities would be performed using existing interfaces.

Before they were shown the set of the 25 activities they would be asked to perform, participants were shown two or three randomly selected activities from the 25, in order to test whether they had understood the instructions. When they confirmed they were comfortable with the activity they moved on to the set they were assigned.

Ten sets of different randomized sequences were created, so every tenth participant would perform the same sequence. For example only participants 1, 11, 21, 31, 41 performed the activities in the same sequence, and only participants 2, 12, 22, 32, 42 performed the activities in the same sequence. The sequence each participant performed can be seen in Appendix G, Section G.2.

The video recordings of the participants pretending they were interacting with the object were analysed to identify their preferred gestures for each activity. Each video was three seconds long, and the countdown before the videos was three seconds. The participants performed the gestures silently, pretending to cause the activity they were reacting to as it was occurring in the animation shown on the screen.

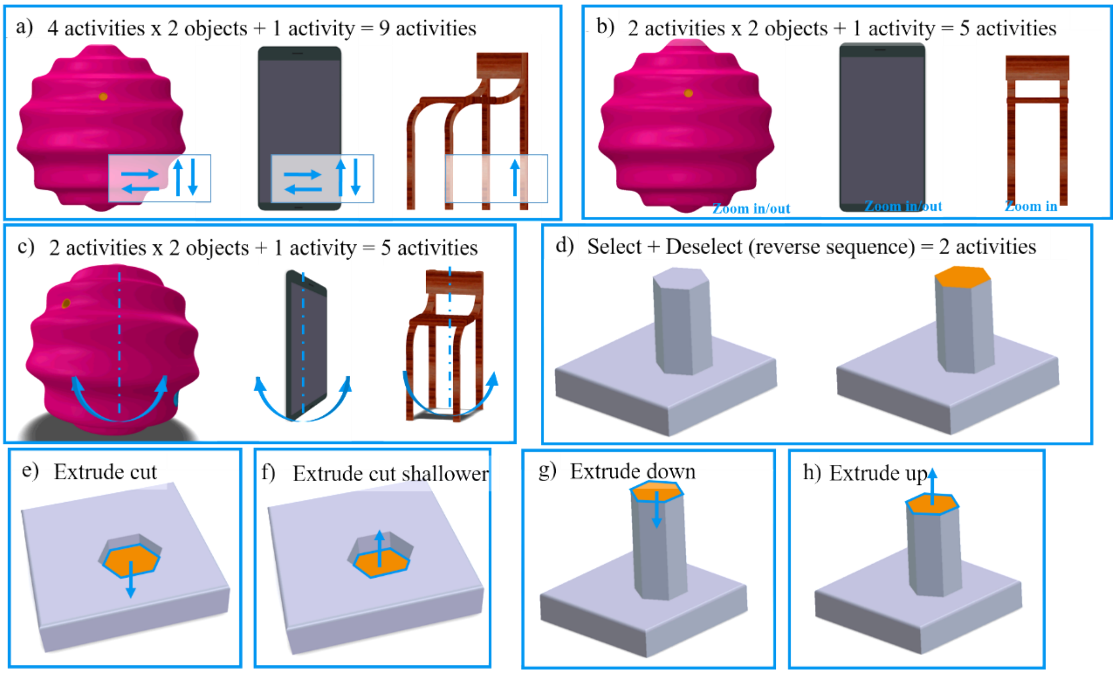


Figure 5-3 : Activities performed in Part 1 of the full study

Three-second time limitation was chosen in order to record the participants' initial reaction, and reduce likelihood of creation of analogies with CAD interaction. User focused studies performed by Wobbrock et al. (2009), Hurtienne et al. (2010), Morris et al. (2014), Piumsomboon et al. (2013), or Khan and Tunçer (2019) did not mention the consideration of time limitations. Eris et al. (2014) and Cash and Maier (2016) observe designers working in a team, an uninterrupted design process, without introducing prompts or time limitations. However, designing in a group would have set a pace naturally. Introduction of explicit time limitation in the study reported in this thesis emulated the pace that can exist in design work naturally.

Following the Pilot Study 1, a decision was made to add the chair, as another object with a recognisable function. The intention was to observe whether the same gesture was used by the same participant during the same activity for all of the objects, rather than interpreting the gesture itself, and thus the chair was used for only three activities, one each for *rotate*, *translate* and *zoom* activity. This was considered suitable, as in the pilot studies the majority of participants used the same type of a gesture to zoom in or out, or translate in different directions. Hence, it is expected that comparing only one direction for each type of activity is sufficient to assess the similarities between the activities for objects that have and do not have a recognisable function.

The participants were asked to use their hands to perform the activity the third time they saw a video of each activity, but were given no further instructions. They were also not told what the goal of the experiment was until both parts were completed. Some participants asked if the object is on the table in front of them, and they were told to interact with it however they perceived it. Participants were also advised that the objects do not have a weight assigned, but are virtual visualisations only.

In Part 2 uninterrupted design process is observed. It consists of two stages that were tested in Pilot Study 2. Participants were shown a presentation on the screen and asked to create the objects shown in images contained in the presentation using their hands. Stage 1 contained a number of predefined steps to reach the final shape, and in the Stage 2 the participants were only shown the final shape and asked to create it. Sequence of activities in Part 2 of the study is shown in Figure 5-4.

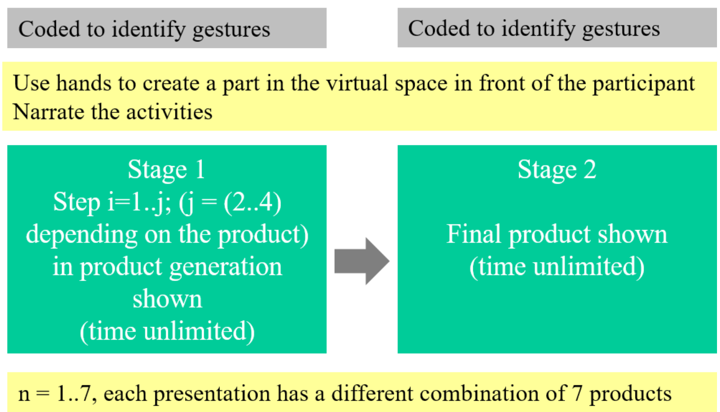


Figure 5-4 : Sequence of activities in Part 2

Instructions for Part 2 of the experiment were the same as in Part 1, except that for the former the participants were explicitly told to imagine the object shown on the screen as if it were a 3D object suspended in the "virtual space" in front of them. Stage one started by asking the participants to create one of the objects shown in Figure 5-5.

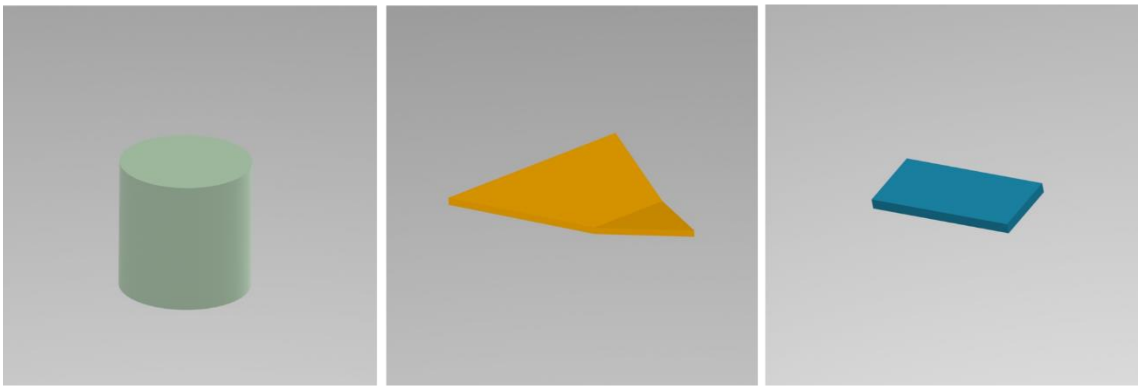


Figure 5-5 : Full study Stage 1, first step for three different parts

Then they were shown a new slide where a slightly more developed object was placed to the right of the initial object, and asked to change the created object to match the photo on the right. For different objects, there were a different number of steps, three for the cup version one and the cup version two, two for the hexagonal plate version one, three for the hexagonal plate version two, and four for the phone cover creation. The steps in the Stage one were used in order to ensure that each participant performed the key activities that were considered to be used frequently in the design process when creating 3D objects in CAD. All of the steps for each of the object progressions are shown in Figure 5-6.

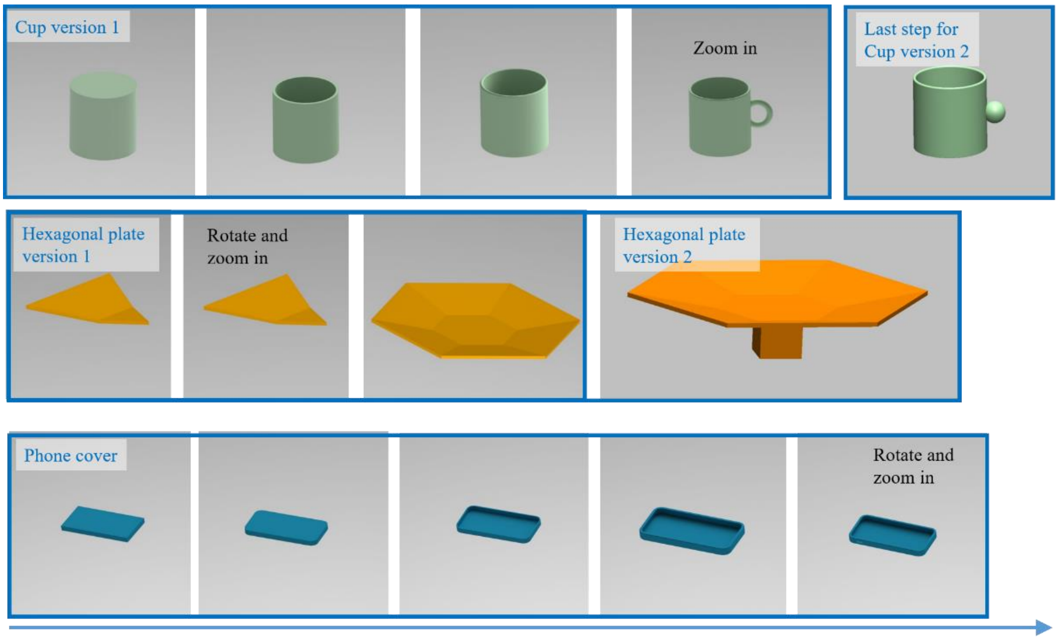


Figure 5-6 : Steps for Stage 1 of the full study Part 2 for all three parts

In Stage 2, participants were shown only one image, showing the final shape. This was one of the products in the Figure 5-7. This stage was designed in order to identify the preferred sequence of steps used to create the shapes, rather than the one following the shapes typically created using solid modelling in CAD, used in Stage 1.

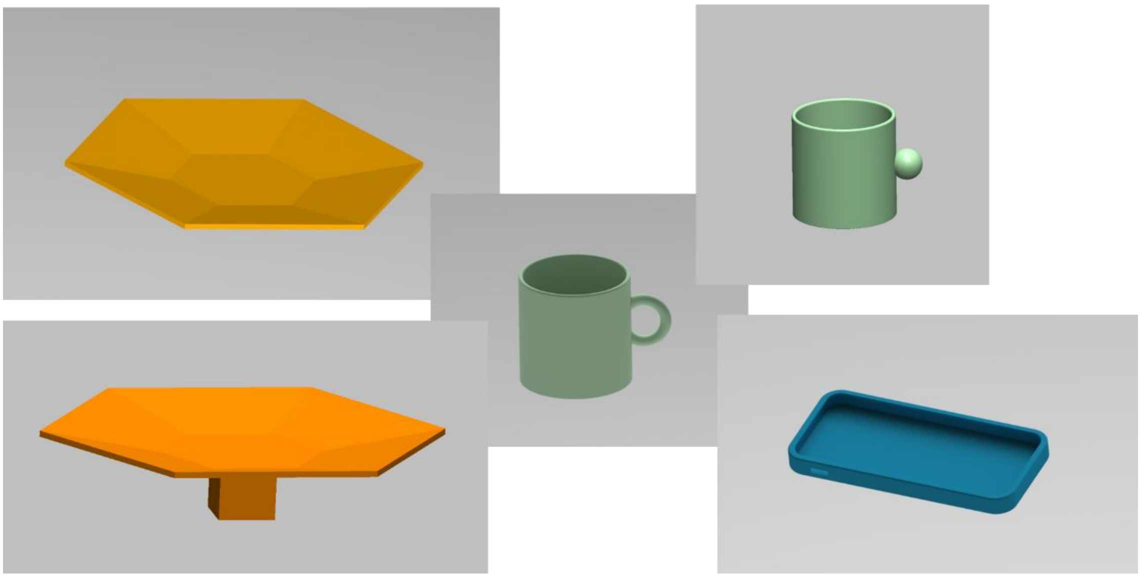


Figure 5-7 : Final products used in Stage two of the Full study

Each participant created two products in total, and the combinations per presentation are given in Table 5-1. Assignment of presentations per participant can be seen in Appendix G, Section G.1.

Table 5-1 : Combinations of objects shown to participants in two stages

Presentation	Stage 1	Stage 2
1	Cup	Hexagonal plate
2	Hexagonal plate	Cup
3	Phone	Cup
4	Cup	Phone
5	Hexagonal plate	Phone
6	Phone	Hexagonal plate
7	Cup version 2	Hexagonal plate version 2
8	Hexagonal plate version 2	Cup version 2

Participants were asked to verbalise their process. The study was allowed to continue uninterrupted if the participants moved through it on their own well. Where needed they were prompted, but prompts were limited to reminders to do things (e.g. “You can rotate the object if you need to.”, “Note that the edge is filleted – how would you do that?”), and not instructions on how to do them.

5.3.2. Equipment positioning

The participants were seated at one end of the table, and a large 2D screen, the animations and presentations containing images of shapes participants were asked to “create” using their hands were shown on, was at the other end of the table, out of reach of the participants. One camera was positioned under the screen. A second camera was positioned at 90 degrees from the first one, on the participants’ left hand side. Camera views are shown in Figure 5-8.

Figure 5-8 : Screenshot of one of the participants taking part in the study (front view on the left, side view on the right)

5.3.3. Participants

Participants in the study were 44 3rd to 5th year Product Design Engineering (PDE) students[5] or graduates at Department for Design Manufacturing and Engineering Management at University of Strathclyde, or the Glasgow School of Art and the School of Engineering and Physical Science at the University of Glasgow. PDE is a five-year course in product or industrial design training students in all aspects of product design process, from research and conceptual design to product manufacture. In it, students develop the skills to create fully functioning new products that are visually appealing and efficiently manufactured and learn to combine virtual and physical design and prototyping. It is professionally accredited by the Institution of Engineering Designers, Institution of Engineering and Technology and Institution of Mechanical Engineers. More detailed reasoning for inclusion of product design students was already given in Section 5.1. Fifteen participants were female, and 29 were male. Seven were left handed, 33 right handed and one participant was ambidextrous. They had 4.9 years of CAD experience on average (cumulative using a variety of CAD software e.g. Alias, AutoCAD, Catia, Creo, Edgecam NX9, Inventor, ProEngineer, Revit, Rhino, Sketchup, Smartplant3D, Solidworks). They also had an average of 1.4 years of design experience in the professional environment, including internships. Their average age was 22.4.

[5] Ethical approval has been sought and approved via Department of Design Manufacturing Engineering Management at University of Strathclyde. The forms are appended in the Appendix C.

5.3.4. Analysis approach

The entire gesture analysis process is illustrated in the flowchart shown in Figure 5-9.

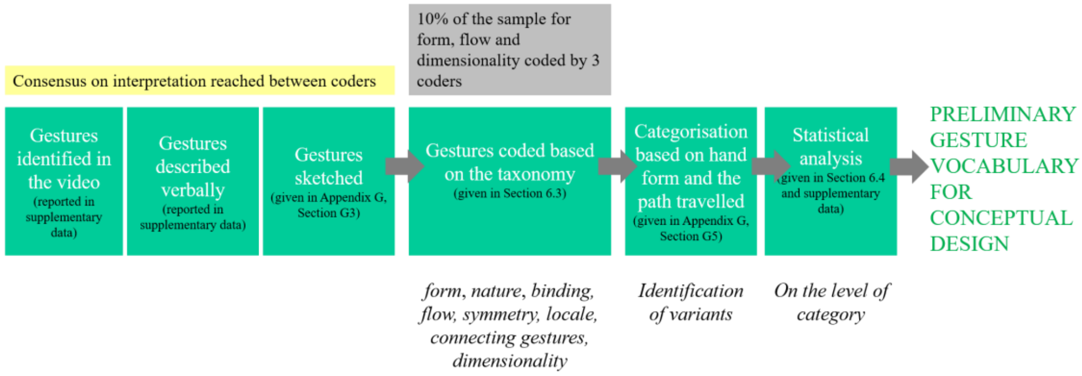


Figure 5-9 : Gesture categorisation process

For both parts of the study, the author first ***identified and described*** the gestures. If one hand was used the description followed the sequence of "Hand activity, axis (palm facing/fingertips facing, plane, open/closed/fingers)". If both hands were used and they were performing the same activity (symmetric), the description followed the sequence of "Activity, axis (palm facing/fingertips facing, plane, open/closed/fingers)". If both hands were used and they performed different activities (asymmetric), the description followed the sequence of "Hand activity, axis (palm facing/fingertips facing, plane, open/closed/fingers)". When both hands were used this naming convention was used to describe the behaviour of left hand first, and then the right hand. Descriptions are given in the supplementary data.

Then each gesture was ***sketched*** on a post it. Gestures were sketched from the point of view of the front camera recording them, but when described the default orientation adopted was the participant's point of view.

Gestures were then ***parsed*** by grouping the post-its, and at this point only the identical gestures were grouped together. Out of the five phases of a dynamic gesture (McNeill, 1992), three were focused on - prestrike hold, stroke and post stroke hold. First and last phase, preparation and retraction, were observed as connecting gestures (described in Section 5.3.4.1.7). The only interpretation involved was when the same gesture was performed in different planes. For example when a participant's the index finger tapped in the horizontal plane to select a horizontal surface and when the index finger tapped in vertical plane to select a vertical surface, these two gestures were considered to be the same, as if the point of view was changed the gesture performed would fundamentally be the same. The collection of parsed sketches can be found in Appendix G, Section G.3. Hand poses comprising different gestures have been collected throughout the sketching process, and a Gesture key was built that summarises standard hand poses used in these gestures. It provides further clarification of what each hand pose sketch represents and aids interpretation of the sketches. The final gesture key can be seen in the Appendix G, Section G.4.

Once this was done, the ***coding*** could start.

5.3.4.1. Taxonomy

Taxonomy, a classification approach that was followed during the coding, was extended from Wobbrock et al. (2009), Morris et al. (2010) and Piumsomboon et al. (2013). It will be described in this section. It is based on a participatory design technique (Schuler and Namioka, 1993) that focuses on elicitation of gestures from the study participants. In the past, this approach was used by Wobbrock et al. (2005) focusing on gestures performed when using surface computing, Piumsomboon et al. (2013) for AR gesture interaction and Ruiz et al. (2011) to identify gestures for mobile interaction. Wobbrock et al. (2009) classify gestures based on their *form*, *nature*, *binding*, and *flow*. Piumsomboon et al. (2013) added *symmetry* and *locale*. This taxonomy has been extended in this thesis and *connecting gestures* (activity performed between the two gestures, in order to identify the connecting motions), and *dimensionality* of gestures (2D or 3D) were also coded. Following sections (sections 5.3.4.1.1-5.3.4.1.8) will define each of the taxonomy classes.

5.3.4.1.1. Form

Based on the form gestures can perform a:

- Static pose – Hand and fingers are static. If both hands are used, if at least one of the hands is moving the pose is considered to be dynamic.
- Dynamic pose – Hand does not move along a path, but fingers do move along their individual paths.

- Static pose and path – Hand and fingers assume a static shape and move along a path.
- Dynamic pose and path – Hand and fingers change shape while moving along a path.

Wobbrock et al. (2009) also included one-point touch and one-point path, as they were using tablets. In the 3D environment, one point touch and one point path are obsolete.

Questions considered during the classification are given in the flowchart in Figure 5-10.

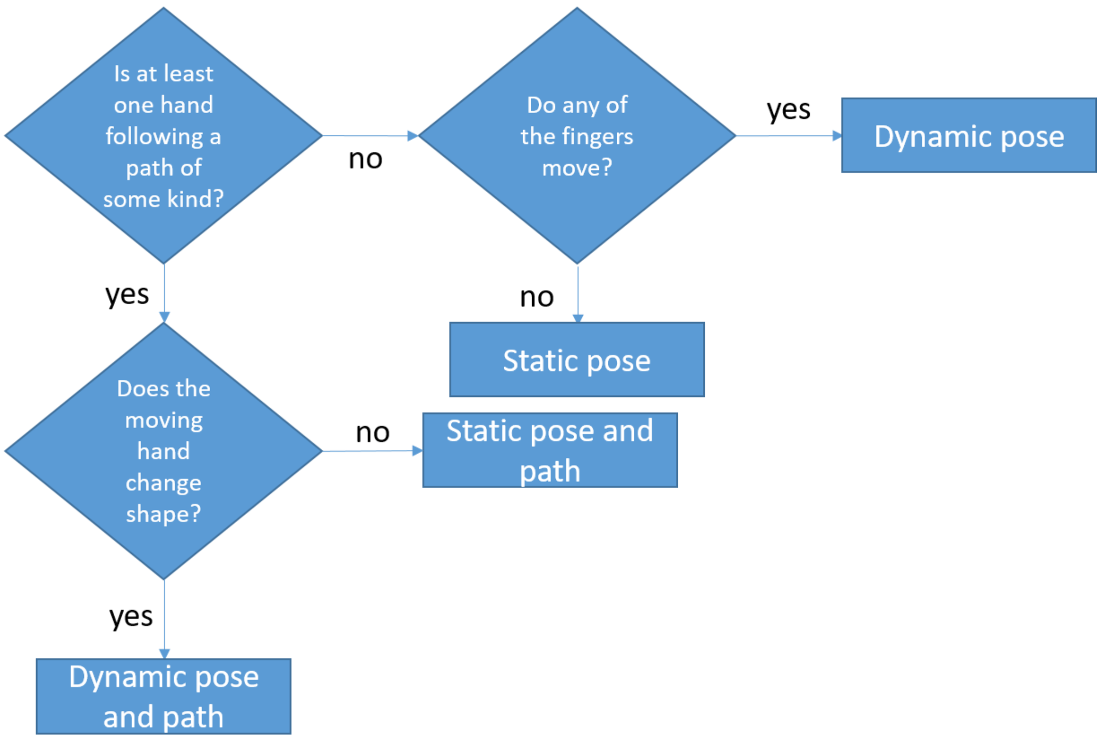
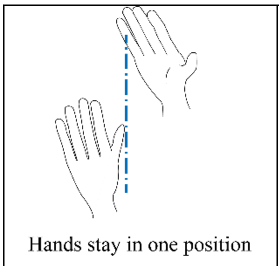
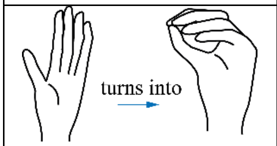
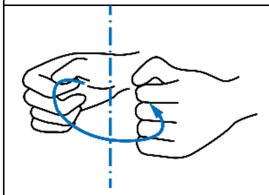
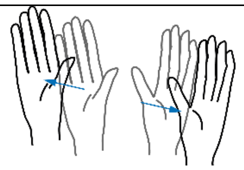
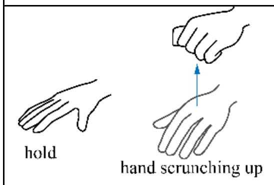
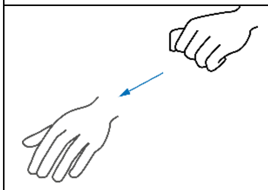


Figure 5-10 : Flowchart illustrating form classification

Examples for each of the form codes are shown in Table 5-2.

Table 5-2 : Examples of form coding

	**Static pose. To rotate both hands stay motionless in one pose.**
	**Dynamic pose.** To zoom out hand turns from open palm into a full hand pinch, but stays in the same spot.
	**Static pose and path (example 1).** To rotate both hands follow a circular path, but the hand shape doesn't change.
	**Static pose and path (example 2).** To zoom in both hands follow separate paths.
	**Dynamic pose and path (example 1).** To undo left hand holds, but right hand changes shape from open hand with palm facing up into a fist while moving upwards in the process.
	**Dynamic pose and path (example 2).** To zoom out, right hand moves forward, and transforms in the process from a fist into an open hand with the palm facing down

5.3.4.1.2. Nature

Wobbrock et al. (2009) classified gestures, based on their nature, as symbolic, physical, metaphoric or abstract. For in-air free form 3D gestures observed in the study, this classification required modification. Classification adopted in this thesis is based on the necessity for a gesture to be learnt prior to use. Observing some of the gestures performed by the participants, some could have been classified as abstract, metaphoric, semaphoric or a symbolic. However, these four types of gestures share a common thread which is that they would have to be learnt prior to use, if they were to be used by a different participant, and do not fully describe the intention of the hand motion without additional information being provided.

In this thesis, gestures requiring additional information to be fully understood were classified as iconic gestures. They encompassed symbolic, semaphoric, metaphoric and abstract gestures. In fact, in the literature, metaphoric gestures were defined as similar to iconic gestures but conveying an abstract meaning (Wagner et al., 2014, McNeill, 1992). However, gestures themselves were only coded as iconic and further classification of if they could also be considered symbolic, metaphoric or abstract was not pursued. It should be noted that gravity was not taken into account i.e. shape does not have weight; it is a virtual shape suspended in air. Gestures classified as physical in previous studies were classified as pantomimic in this thesis. This was done due to the context, as the interaction with the 3D object in the imagined virtual space was often equal to what hand motions would be if the same interaction as performed in the physical world i.e. physical activity was pantomimed in the virtual world. Third class of metaphorical pantomimic gestures was introduced to describe pantomimic gestures that conveyed a metaphoric meaning.

In summary, gestures were classified as:

- Pantomimic – If hands are performing the motions which would without any further information result in the activity performed.
- Metaphorical pantomimic - If hands are performing the motions which would without any further information result in a familiar activity in the physical world, but that has a methaporic meaning in the virtual world because additional meanings were added to it.
- Iconic – If more information is needed to fully understand the gesture or it is ambiguous in any way i.e. if learning was required that a gesture indicates a certain activity.

Questions considered during the classification are given in the flowchart in Figure 5-11.

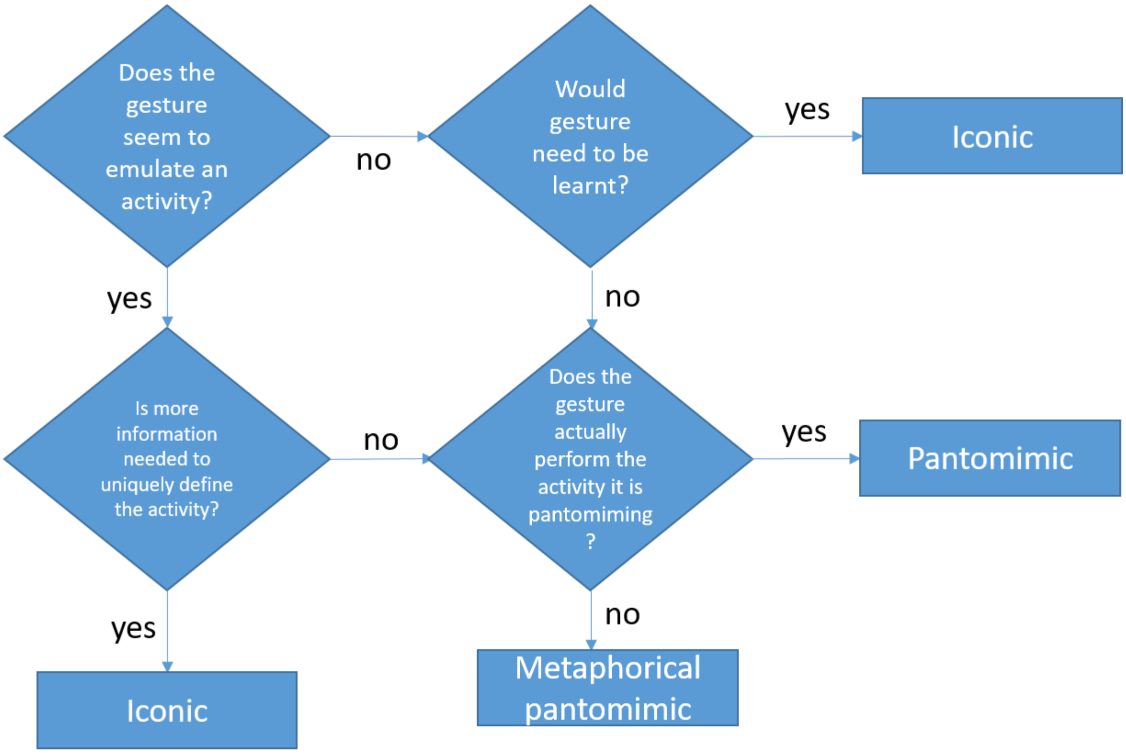
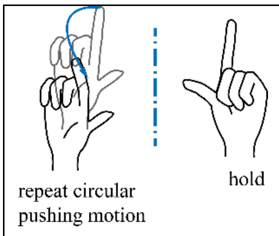
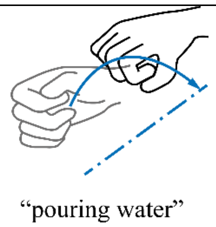
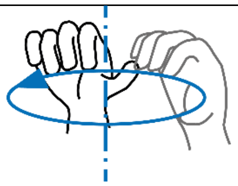
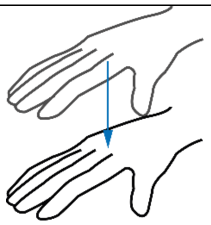


Figure 5-11 : Flowchart illustrating nature classification

Examples for each of the form codes are shown in Table 5-3.

Table 5-3 : Examples of nature coding

	**Pantomimic.** To rotate left hand replaces an axis, and right hand spins the object around like a globe, or a basketball.
	**Metaphorical pantomimic.** To lift the bottom of the cut higher up, water is poured so the level of “water” rises. It was never indicated that the water was in the cut, therefore additional meaning seems to have been added to the visual by the user.
	**Iconic (example 1).** To fillet an edge a hand traces it. While this may be considered to be a pantomimic gesture as you may form an edge of a sculpted cup that way, it may as well be just tracing a shape and to pick one of the two more information is needed.
	**Iconic (example 2).** To translate an object down hand is moved downwards, parallel to the ground with an open palm. This may be understood as translate down, but it may also indicate change of height, compressing something, moving only one surface down etc. Without more information it is hard to say which option is more likely.

5.3.4.1.3. Binding

Wobbrock et al. (2009) and Piumsomboon et al. (2013) provide four classification options for binding classification of objects:

- object-centric (location defined wrt object features),
- world-dependent (location defined wrt world features),
- world-independent (location can ignore world features), and
- mixed dependencies (world-independent plus another).

In this study, all gestures were object-centric due to specific guidance given to the participants to focus on the object only.

5.3.4.1.4. Flow

Wobbrock classified gestures in terms of flow as discrete where response occurs after the participant acts, or continuous where response occurs while the participant acts.

Again, due to study composition and instructions to participants to perform gestures along with the animation viewed, gestures were continuous in all instances.

5.3.4.1.5. Symmetry

In terms of symmetry Piumsomboon et al. (2013) classified gestures as unimanual (and then further as dominant or non-dominant depending on their handedness) and bimanual (and then further as symmetric or asymmetric).

While differences in use of dominant and non-dominant hands were noticed during the study, they did not influence the goal or meaning of the gesture performed, only its orientation i.e. mirror image of the same gesture would be performed using opposite hand in some cases. This is why hand dominance has not been considered in this study, the gestures were simply grouped together and the version of the gesture performed by participants with the dominant right hand had been recorded. Left-handed version would be a mirror image. As described in Section 3.2 handedness was only significant if it was important for the role of a gesture in an interface or fundamentally changed the type of the gesture observed.

Symmetric gestures were further classified in this study as symmetric mirrored (both hands perform the same path but mirrored) or symmetric copied (both hands have the same form and follow the same path).

In this study, concerning symmetry, gestures were classified as:

- Unimanual,
- Bimanual symmetric mirrored,
- Bimanual symmetric copied,
- Bimanual asymmetric.

5.3.4.1.6. Locale

Observing the locale, the gestures could be performed on the surface or in-air, and these classes were identified from the performed gestures. On-the-surface gestures, in the context of this study, were those in which some participants used the table in front of them as an aid.

5.3.4.1.7. Connecting gestures

If a language of gestures for design were to become a new interaction paradigm for 3D modelling, the transitions between the gestures would become more important. Thus, a code was added describing the gesture motions between two distinct gestures, in Part 2 of the study only, as Part 2 included uninterrupted designing.

Three different activities took place:

- Hands remain in previous position
- Hands resting on the table
- Open palms vertical in air.

5.3.4.1.8. Dimensionality

Participants viewed animations on a 2D screen, and performed gestures in 3D space. The pilot studies (see Appendix B) showed that the participants perceived the visuals as three-dimensional, and did perform 3D in-air gestures. In the full study, participants were explicitly asked if they perceived the object in the video as a 3D object suspended in front of them. 86% of the participants confirmed that this was the case. Two participants did not know how they perceived the objects, one disagreed and two strongly disagreed. Where participants stated they did not imagine objects as 3D or did not know how they imagined the objects, gestures were coded for dimensionality.

A gesture was considered 3D if the participants hands "broke" the plane e.g. used more planes than the vertical plane the image was shown in.

Gestures were coded as 2D if:

- All of the motions were performed in one plane that matched the plane the gestures were shown in (vertical plane of the wall the screen was on), and participants appeared to be interacting with a touch screen.
- All of the motions were performed on the table (e.g. the participant pushed the imaginary object forward with their palm touching the table).

Gestures were coded as 3D if:

- Participants seemed to interact with an object suspended in the air in front of them and used multiple planes with at least one part of the hand they used for the interaction with the object.
- Gestures were performed as if the imagined object was located on the table but was in 3D (e.g. hold the object's imaginary vertical axis and "rotate it" by touching the "sides of the object").

This is summarised in the flowchart shown in Figure 5-12.

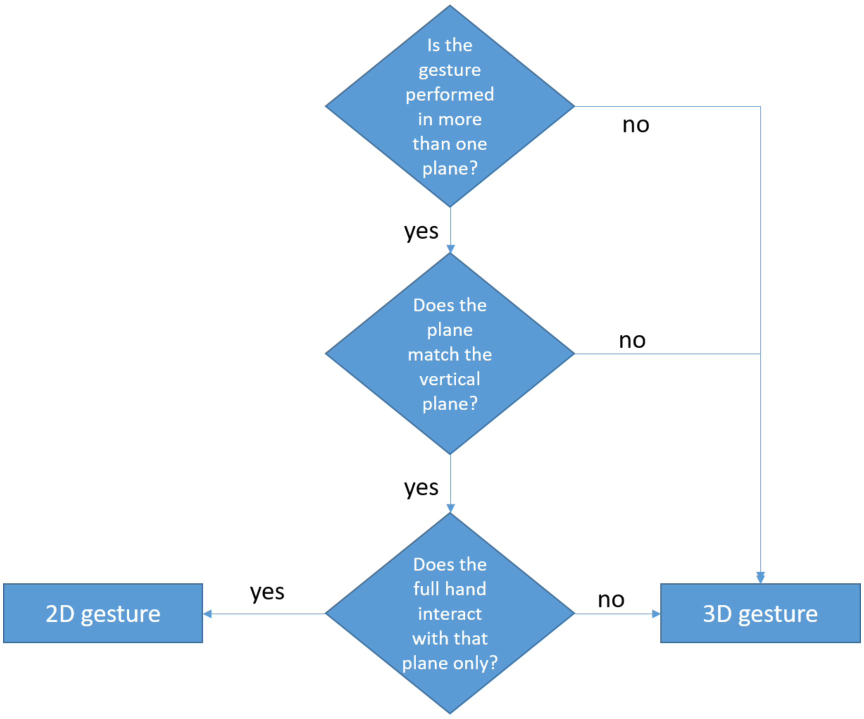
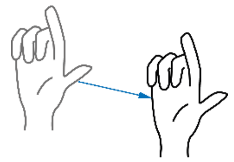
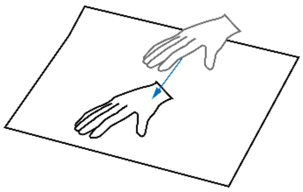
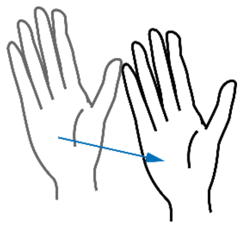
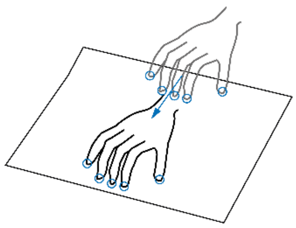


Figure 5-12 : Flowchart illustrating dimensionality classification

Examples for each of the dimensionality codes are shown in Table 5-4.

Table 5-4 : Examples of dimensionality coding

 1, 2 or 3 fingers	**2D (example 1).** To translate an object left, hand is indication it is touching the vertical plane with one, two or three fingers. Gesture appears as if it is interacting with a touch screen and it is not giving the object any depth.
	**2D (example 2).** To translate up, gesture is sliding an imaginary object forwards, but is fully touching the table, not allowing for any other dimension for the object, other than the front face in the vertical plane.
	**3D (example 1).** To translate an object left, right "side" of the object is pushed by the open palm, giving it depth.
	**3D (example 2).** Gesture is sliding an imaginary object backwards to "translate down" in one plane, but the gesture is grasping the object in a plane perpendicular to it, using a plane that did not exist in the visual representation of the activity.

5.3.4.2. Categorisation

Once all the gestures were coded (coding outcomes can be reviewed in Chapter 6), they were ***categorised and analysed for patterns and relations***. Sketches were then assigned unique identifiers. Categorisation was based on similarity. Gestures that performed the same activity following the same path were grouped in the same category. However, each variant was given its own code expressed by a decimal value. The coders were trained to apply the same approach to interpretation of gestures.

Each unique activity was given a unique code and number, and the numbers have the form of nn.n, e.g. TL01.1. The letters depict the activity, two numericals before the decimal space depict the category, and the numerical after the decimal space depicts the variant within that category. The letter code is the same for each group of gestures and the list of the letter codes for both parts can be seen in Table 5-5.

Table 5-5 : Codes for activities

Part 1		Part 2	
TL	Translate left	Drw	Draw
TR	Translate right	Ext	Extrude
TU	Translate up	ExtC	Extrude cut
TD	Translate down	Ben	Bend
ZO	Zoom out	MulPat	Multiply/Pattern
ZI	Zoom in	Und	Undo
RCW	Rotate clockwise	Res	Resize
RCCW	Rotate counterclockwise	C/SPl	Create/Select Plane
D	Deselect	EExt	End the Extrude
S	Select	Fil	Fillet
EC	Extrude cut	F/In	Fill In
ECS	Extrude cut shallower	Scl	Scale
EU	Extrude up	Zoom	Zoom
ED	Extrude down	Select	Select
		Rot	Rotate
		Sph	Sphere
		Slice	Slice
		Scul	Sculpt
		Join	Join
		Loft	Loft
		Tra	Translate
		Copy	Copy
		Snap	Snap fingers to sketch
		Stick	Stick

Images containing sketches of all gestures and codes assigned to them can be reviewed in Appendix G, Section G.5.

As an illustration of the categorisation, a specific example is worked through below.

Translate Left activity was used as an example and it is illustrated in Figure 5-13. The first gesture category is the one where a hand translation was performed by tracing a hand along a horizontal line from right to left, and the same gesture was performed with six varieties – TL01.1-6. The difference between them is the shape the hand forms. None of hand shapes indicated that the hand “held” the object being moved, which was the case for TL02.1-6, while the same horizontal right to left path was followed the hand pinched or grasped or otherwise encircled the object being moved. Similarly, when the same horizontal path was followed with both hands, “holding” the object or not, they were assigned individual codes, TL03.1-4 and TL04.1-4 respectively. A similar approach was identified in work by Wobbrock et al. (2009) and Piumsomboon et al. (2013), however they have not presented the sub-variants, and did not differentiate the gestures in terms of the object being held. Wobbrock et al. (2009) also draw upon the work of Beringer (2001) who finds that pointing is often performed using arbitrary number of fingers, hence concluding that as long as a full hand is not used a number of fingers can be disregarded and categorised as a same gesture. This approach is adopted in this thesis. Additional justification for disregarding the number of fingers used is that they do not fundamentally change the gesture performed, while the use of the full hand occasionally can indicate a different activity. Finally, although the intention of this work is to identify the gestures in isolation from the available technology, if the current commercially available tracking and recognition systems are considered, even the basic widely available ones such as LEAP differentiate between the numbers of fingers can be programmed to assign them to any desired activity.

The main code assigned TL01, TL02, TL03 or TL04 was kept the same, as the gestures were fundamentally the same and corresponded to all of the taxonomy categories. Variants described by the decimals provide further illustration of the hand pose beyond taxonomy, and all variants under the same category would fall under the same taxonomy classifications as the category would. The only taxonomy class that does not entirely follow this approach is dimensionality, as the variant gestures of seven participants who were not sure if they perceived objects as 3D or stated that they did not perceive objects as 3D were further classified as 2D or 3D. In some instances, different variants under the same category would be classified differently in terms of dimensionality. For example, TL 01.1 could be a 2D gesture, while TL01.2 uses more than one plane and is likely to be a 3D gesture. However, due to 36 out of 44 participants stating 3D objects were perceived, and the technological developments allowing better use of 3D/VR/AR spaces, dimensionality classification was not considered to warrant inclusion in these cases. Same approach was used in coding gestures TL05-07, and for them either the table was used as a locale (for TL05 and TL06), or the path of motion was slightly different (arc for TL07).

Part 1 - Translate Left

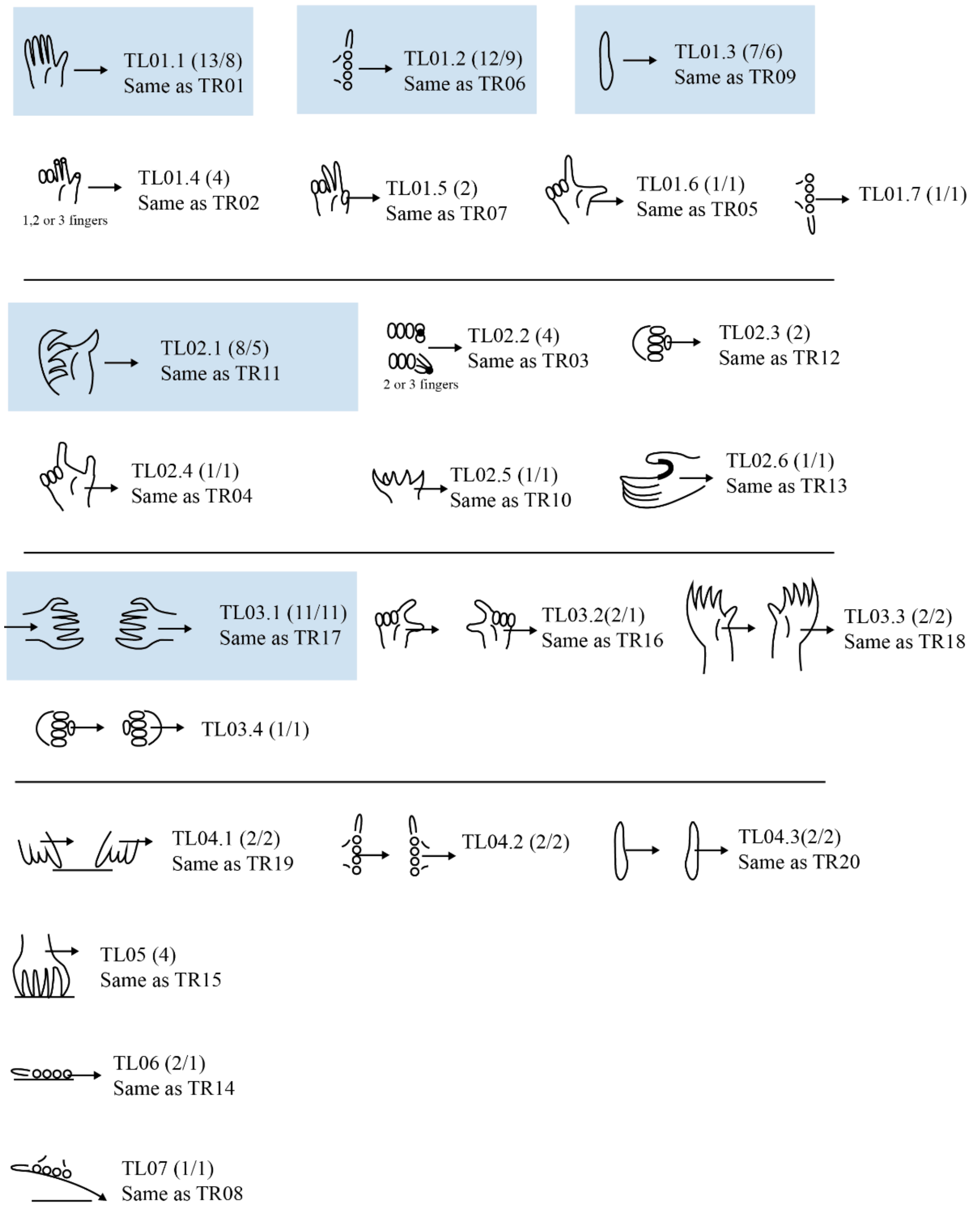


Figure 5-13 : Part 1 Translate Left gesture coding

For Part 2 the exception was made for the gestures where non-dominant hand was "holding" the shape while the dominant hand was manipulating the shape, and in these cases no differentiation was made in terms of the hand pose used to "hold" the object. For example, grasping, pinching, open hand, U shaped hand were all considered to perform the holding function. Different variants used were all sketched, and variations are indicated using the word OR between them. This decision was made because at this point the decision on if "hold" would be used in the implementation or not will not be decided on, and this level of detail was not necessary.

Then Agreement Rate (AgR; normally this is referred to as AR in the literature, but in this thesis AgR is adopted as an acronym in order to differentiate it from Augmented Reality), Chi Square and Fleiss Kappa were calculated and analysis was performed for all of the identified gestures. The most frequently used gestures that show statistical significance will be used to form a language of gestures for conceptual design. This is explained in detail in Chapter 6, Section 6.3.

At the end of the classification and categorisation process, results of which are given in Sections 6.1, 6.2 and 6.3, a consensus set of gesture vocabulary for form creation was built. The consensus set is a collection of the gestures elicited from the participants that have occurred the most frequently. The number of repetitions was statistically analysed to ensure their significance and that they did not happen by chance. Details of the statistical analysis approach are given in Section 6.4.

5.3.5. Evaluation of the consensus set

Once the consensus set is built, it will be evaluated by ten non-designers. This will be done in order to remove any bias introduced by the training the 44 designer participants received through their education and design experience.

Evaluation consisted of two parts, Part 1 was the abstract evaluation and Part 2 was VR evaluation. Part 1 aimed to evaluate the gestures in isolation from the technical implementation, in order to avoid the effects of application technology on the gesture selection. However, it was also considered valuable to assess how implementation affects the gesture use, and Part 2 evaluated gestures implemented in a preliminary

VR application developed at the University of Strathclyde. In Part 2, evaluation questionnaire will keep the questions about the gestures and application capabilities separate. Half of the participants performed VR based evaluation first, and the other half performed the abstract evaluation first, in order to reduce the influence of one on the other in the results.

Both questionnaires can be found in the Appendix H, Section H.3. The questions were adapted from Wobbrock et al. (2009) and Piumsomboon et al. (2013) to better fit the needs of the evaluation study, and two questions were added to the second part of the evaluation.

In Part 1 participants emulated the use of gestures the researcher had shown them, along with images of the object being manipulated and description of what element of the object is being created, modified or manipulated using the gestures. Then they answered the questions designed to evaluate appropriateness of the gesture for the activity, and ease of performance:

- Was the gesture you just imitated a good match for the current activity (i.e., would that gesture be a good way to execute that activity)?
- Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture’s physical action)?

A seven point Likert scale was used for the responses: Strongly Disagree, Disagree, Mildly Disagree, Neither Agree nor Disagree, Mildly Agree, Agree, Strongly Agree. Participants were also asked to provide any further comments they had at any point of the process. During the analysis, numerical values were assigned to the Likert scale responses to enable the values to be plotted on a graph and compared between different gestures. Strongly Disagree corresponded to a value of 1, Disagree to a value of 2 and so on. Highest value was 7 for Strongly Agree. Average value of 1-3 was a range of strong to mild disagreement. Average values around 4 indicated that participants neither agreed nor disagreed with the statement. Average values between 5 and 7 indicated mild to strong agreement.

For activities where more than one gesture was being evaluated, after they have performed the entire set, they were asked to choose their preferred gesture among the offered gestures.

This approach to evaluation is common in the field of user based gesture elicitation, however at times evaluation is performed immediately after the elicitation, by the same participants that were involved in the elicitation (Piumsomboon et al., 2013). Typically criteria for gesture evaluation were: easy to perform, intuitive or natural, memorable, comfortable, low perceived fatigue, discoverability, simplicity (Koutsabasis and Vogiatzidakis, 2019). In some studies evaluation was performed by a small number of experts who viewed representative samples (level of representativeness was based on clarity of the samples), assessing which samples explained the referents better determining which gestures were a good match for the intended purpose, or how complete the conveyed information was (Khan and Tunçer, 2019). As the objective of the study performed as a part of this thesis is to elicit natural and intuitive gestures, the decision was made to use non-designers for evaluation, and ask the participants if they found the gesture appropriate and easy to perform directly and not interpret their statements. It was considered that the study setup would ensure the intuitive and natural gestures are elicited, and parameters such as memorable, comfortable, low perceived fatigue, discoverability or simplicity become prominent in the application, and would be considered in the future, when the requirements of the application technology are known.

In Part 2, a limited number of gestures were tested in a VR application developed by a system developer following the specification given to them by the researcher, as a part of the Route to Impact project on “Natural gestures VR/AR CAD interaction system”. The system employs HTC Vive headset with a LEAP sensor mounted on it, Unity, and Steam platforms and a high specification desktop computer. HTC Vive with a LEAP sensor was at the time of evaluation (2019) a mainstream PC-VR for gamers providing precise, 360-degree headset tracking. Description of the system and all the activities it can perform are given in Appendix H, Section H.4. Sixteen most frequently repeated gestures for activities were shared between the application and the consensus set:

- Four *translations left* and *right* (TLR1, where TLR stands for Translate Left Right, combining TL01.2 and TR01.2, TLR2 combining TL01.3 and TR01.3, TLR3 combining TL01.1 and TR01.1, and TLR4 combining TL03.1 and TR03.1),
- Four *translations up* and *down* (TUD1, where TUD stands for Translate Up Down, combining TU01.6 and TD01.1, TUD2 combining TU01.1 and TD01.5, TUD3 combining TU01.2 and TD01.2, TUD4 combining TU02.2 and TD02.1),
- Four *rotations clockwise* and *counter-clockwise* (R1 combining RCW01.1 and RCCW01.1, R2 combining RCW01.2 and RCCW01.2, R3 combining RCW01.3 and RCCW01.3, R4 combining RCW02.1 and RCCW02.1),
- Four *zoom in* and *zoom out* activities (Z1 combining ZO01.1 and ZI01.1, Z2 combining variations of ZO04.1 and ZI02.1, Z3 based on ZO05.1, Z4 combining ZO04.2 and ZI02.2).

Gestures for these codes can be seen in Appendix G, Section G.5. For these sixteen activities, participants were asked to answer the questions designed to evaluate appropriateness of the gesture for the activity, and ease of performance regardless of implementation qualities within the system, satisfaction with the result of the activity, and difficulty or ease of the use of the application:

- Was the gesture you just imitated a good match for the current command (i.e., would that gesture be a good way to execute that command).
- Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture’s physical action)?
- Was the gesture resulted in the action you expected?
- How difficult is it to perform the gesture (considering technology)?

Again, a seven point Likert scale was used, the participants were asked to provide any further comments at any point, and if more than one gesture was used for any single activity, they were asked to select a preferred one.

Following the completion of the evaluation process, the results will be analysed and used to create a variation of the consensus set.

5.3.6. Study robustness

To test the study robustness in terms of being applicable to a variety of shapes, some of the activities were performed repeatedly, on different objects. *Zoom in/out, Rotate cw/ccw,* and *Translate up/down/left/right* were repeated for the irregular sphere and the phone, and *Zoom in*, *Translate up*, *Rotate cw* were repeated for the chair, phone, and sphere. The objective was to observe if the shape of the object being manipulated or its recognisability have an effect on the gestures used for the interaction.

If the participant performed the same gesture for the same activity for different objects, it was assumed that the shape of the object does not affect the gesture use. If they were different, there may be an effect.

Recognisability was defined in terms of the function of an object. Gestures participants used to perform the same activities on the objects that have a specific function in physical world were observed. The sphere was the only object that was not used in everyday life and did not have an associated function. Therefore, it was assumed that if recognisability was not playing a part in the gesture interaction with the object, a larger proportion of gestures used to interact with the sphere would be performed in the same manner as the gestures used to interact with the phone and the chair.

The activities participants performed were compared to their statements in the questionnaire, in order to explore what the users' perceptions of their activities were.

5.3.7. Object creation workflow

In Part 2 of the study each participant was asked to create two of the three objects: a cup with a handle, a hexagonal plate, or a mobile phone case. Cup and the hexagonal plate had two variants, which were identical until the last step in which the cube and sphere were introduced to the product being built in order to explore which gestures the participants would use to create solid shapes in the context of a more complex product.

In the first stage key steps of the creation of the product were guided and while participants were free to use any gesture they wanted, they were asked to, in the example of cup creation, create a cylinder first, then hollow it, then filet the edge and so on (as shown in Figure 5-6). It was thought that due to the number of steps involved in a product creation, if the participants were using their imagination to visualise the intermediary steps, they might lose track of the steps and skip some. The Stage 1 ensured the key activities for gesture identification were performed and gestures recorded. However, it also followed one of the most common workflows used in solid shape design if a CAD system were to be used.

In the Stage 2 only the final product was shown, and participants were asked to create the products without being given any particular instructions. This was done to enable the observation of the participants' preferred workflow, and the sequence of activities in it. The first stage pushed the participants towards the established CAD workflow, focusing on the solid modelling design process. It was expected that in the second stage they would follow the same workflow if it was genuinely the most intuitive, and that if that was not the case, different activities or sequences of activities would take place.

To reduce the effect of potential adoption of the practices from the first stage to the second stage, half of the participants performed the two stages in reverse order. While giving the instructions to the participants they were instructed to disregard any potential technical difficulties they may imagine a system might have, and to assume that the room they were sitting in would know exactly what they are trying to do and that everything was possible and all activities would be recognised without any issues. Activities were coded, classified and grouped, and compared for the same products for two stages. The gestures collected in the Part 2 of the study were also added to the gesture list, which was classified and categorised in order to create a consensus set of gesture vocabulary for form creation. Its creation is detailed in Sections 5.3.4.1 and 5.3.4.2.

5.3.8. Inter-coder reliability

To assess the coder reliability Krippendorf's alpha measure of reliability was used. It is considered a suitable measure due to its generality and ability to be used regardless of "the number of observers, levels of measurement, sample sizes, and presence or absence of missing data" (Hayes and Krippendorff, 2007). It results in a statistical measure of agreement among coders of data and indicates their reliability. The author coded 100% of the gestures recorded. Two additional coders were asked to code 10% of the fields where gestures required higher levels of interpretation. The coders were PhD students, research and teaching assistants at DMEM. They were both in their final year of the PhD. They have previously completed a MEng in PDE and their PhD topics were in the field of product design. Coding guide used for the full study, an improved version built based on the coding guide for the pilot studies given in Appendix D, can be found in Appendix E.

An excel table with codes was provided, shown in Figure 5-14, along with the sketches of gestures performed for each of the activities (same gestures were grouped, as indicated by the codes in the far right columns in the table, but otherwise not interpreted in any way, and were coded individually). They could access all the videos of the gestures being performed (provided in the supplementary data), and sketches of them (provided in the Appendix G, Section G.5). Time stamps for the videos were in columns C and D, to help find them quickly.

Only the fields highlighted in yellow and pale red (aspects relating to form, flow and dimensionality) were to be coded, as they were the ones where higher levels of interpretation of participants' intentions was required and hence multiple coders were required to reach a consensus. A statistical measure of agreement among coders was used to measure this. These were:

- 2D/3D (fields highlighted in pale red – for the rest the participants have stated they have imagined shapes as 3D objects suspended in front of them already).
- Form (fields highlighted in yellow in column Y)
- Gesture type (fields highlighted in yellow in column AA)

Codes provided by all three coders for 10% of the sample were collated and inter-coder reliability was calculated using Krippendorff's Alpha reliability estimate.

Gesture coded looking from above, participant point of view																					
Gestures drawn as seen on camera					One																
Needs 2nd coder					Both													Iconic might be Semaphoric			
				1 hand: Hand activity, axis (palm facing/fingertips facing, plane, open/closed/fingers) symmetic: Both Activity, axis (palm facing/fingertips facing, plane, open/closed/fingers) assymetric: Hand activity, axis (palm facing/fingertips facing, plane,	One/Both	Right/Left/Both/Both same actvitiy/Same activity mirrored	Unimanual/Bimanual symmetric/Bimanual assymetric	What is the step of the activity trying to achieve		What is the activity trying to achieve		Cup/Hexagonal plate/Phone/Chair/Console	y/n/(n/a)	Gesture is 3D if hands "break" the plane (use more than the		No transition (hands stay in previous position)/Hands resting on table (while thinking about next step)/Open palms vertical in air			Iconic when needed to be predefined, pantomimic	Unique number	same as
Part	pg code	time c1	time c2	gesture	No. har	Handed	Bimanual etc.	activity step	activit	activity type	activity type r	model	staged	2D/3D	Presen	Between gestures (aft	Form	Gesture type			
1	P14G21	01:49	01:52	Right hand push forward (Palm facing front/fin	One	Right	Unimanual	n/a	n/a	Zoom out	n/a	Phone	n/a		n/a	n/a				ZO29	ZI30
1	P14G24	02:07	02:11	Right hand translates up (Palm facing front/Fin	One	Right	Unimanual	n/a	n/a	Extrude cut shallow	n/a	Console	n/a		n/a	n/a				ECS21	
2	P14G27	00:30	00:34	Left hand hold (Palm facing down/fingers facin	both	Both	Bimanual assymet	Bend - Hold one side and pu		Bend sides		Hexagonal plat	y		2	Hands resting on table				Ben02	
2	P14G31	00:57	00:59	Right hand completes 3 tap hops to the left (Pa	both	Same actv	Bimanual symmet	Undo - Fold them all back ou		Undo		Hexagonal plat	y		2	Hands resting on table				Und18	
1	P15G08	00:42	00:45	Left hand hand hold (palm facing right, in vertic	Both	Both	Bimanual asymme	n/a	n/a	Select	n/a	Console	n/a		n/a	n/a				S07	
1	P15G13	01:02	01:04	Left hand holds (Palm facing down/fingers faci	Both	Both	Bimanual asymme	n/a	n/a	Extrude up	n/a	Console	n/a		n/a	n/a				EU05	
1	P15G22	01:58	02:02	Left hand translates left in a slight curve(Palm f	One	Left	Unimanual	n/a	n/a	Translate left	n/a	Phone	n/a		n/a	n/a				TL08	TR08
	P15G27	00:31	00:33	Left hand hold (Palm facing up/Fingers facing ri	both	Both	Bimanual asymme	Fillet the edges		Fillet		Phone	y		3	Hands resting on table				Fil02	
	P15G30	01:05	01:07	Left hand hold (Palm facing up/Fingers facng rig	Both	Both	Bimanual assymet	Rotate		Manipulate		Phone	y		3	Stay in previous position				Rot01	
1	P16G05	00:19	00:22	Right hand rotates cw (Palm facing up/fingers f	One	Right	Unimanual	n/a	n/a	Rotate cw	n/a	Sphere	n/a		n/a	n/a				RCW01	RCCW01
1	P16G07	00:30	00:33	Both hands pull back (Palms facing eachother/f	Both	Same acti	Bimanual symmet	n/a	n/a	Zoom in	n/a	Phone	n/a		n/a	n/a				ZI23	
1	P16G16	01:10	01:15	Both hands rotate cw (Palms facing eachother;l	Both	Same acti	Bimanual symmet	n/a	n/a	Rotate cw	n/a	Phone	n/a		n/a	n/a				RCW19	RCCW16
1	P16G18	01:16	01:19	Right hand translates down (Palm facing left/fi	One	Right	Unimanual	n/a	n/a	Translate down	n/a	Phone	n/a		n/a	n/a				TD04	TU05
	P16G30	00:53	00:55	Both hands trace the edge (Palms facing back/f	both	Same actv	Bimanual symmet	Fillet - Soften the edges		Fillet		Cup	y		4	Hands resting on table				Fil14	
	P16G38	01:45	01:47	Both hands moving apart (Palms facing front/Fi	both	Same actv	Bimanual symmet	Zoom in		Manipulate		Phone	n		4	Stay in previous position				Zoom06	
1	P17G01	00:00	00:03	Both hands translate up (Palms facing up/finge	Both	Same acti	Bimanual symmet	n/a	n/a	Translate up	n/a	Sphere	n/a		n/a	n/a				TU16	TD12
1	P17G09	00:39	00:41	Left hand hold (palm facing down, in horizonta	Both	Both	Bimanual asymme	n/a	n/a	Deselect	n/a	Console	n/a		n/a	n/a				D07	
1	P17G17	01:18	01:22	Both hands translate down (Fingers facing fron	Both	Same acti	Bimanual symmet	n/a	n/a	Translate down	n/a	Sphere	n/a		n/a	n/a				TD13	
	P17G27	00:05	00:10	Left hand hold (Palm facing forn/fingers facing	both	both	Bimanual assymet	Bend the corner of the trian		Bend the edge		Hexagonal plat	y		5	Hands resting on table				Ben07	
	P17G30	01:08	01:10	Left hand hold (Palm facing down/Fingers facin	both	both	Bimanual assymet	Cut it		Undo		Hexagonal plat	y		5	Stay in previous position				Und07.1	
	P17G35	01:32	01:36	Left hand hold (Palm facing down/Fingers facin	both	Both	Bimanual assymet	Extrude cut - Hollow it		Make a shell out of it		Phone	n		5	Hands resting on table				ExtC08	
1	P18G05	00:19	00:21	Both hands slide closer together (Palm facing fr	Both	Both	Bimanual symmet	n/a	n/a	Zoom out	n/a	Phone	n/a		n/a	n/a				ZO01	ZI01
1	P18G25	02:11	02:16	Right hand push forward (Palm facing front/fin	One	Right	Unimanual	n/a	n/a	Zoom out	n/a	Sphere	n/a		n/a	n/a				ZO29	ZI30

Figure 5-14 : Example of coding table given to the coders

5.4. Summary

Full study methodology has been covered in this chapter, reporting on the reasoning behind the chosen research approach, based on user based participatory design technique and taxonomies established in the HCI field of research.

User based gesture elicitation method was initially developed by Wobbrock et al. (2005), and further developed by various research groups exploring user based gesture elicitation in varied applications in the field of HCI.

The research approach and taxonomy have been adapted to the needs of the field of the study of this thesis i.e. natural and intuitive in-air gesture identification for conceptual design. These changes include changes to taxonomy for the nature of gestures (iconic, pantomimic and manipulative pantomimic), symmetry (decomposition of bimanual symmetric gestures into bimanual symmetric mirrored and bimanual symmetric copied gestures) and the addition of two taxonomy categories - connecting gestures and dimensionality.

The two-part study design has been tested and refined via two pilot studies. The outcomes of the pilot studies confirmed that the study design is largely appropriate and introduced a number of changes and additions to the study design, in order to ensure comprehensive data collection. The LEAP sensor was removed from the study design due to insufficient range of capture, and a second camera was added to allow for multiple viewpoint recording, as a contingency.

The full study methodology is reported in this chapter, including the details describing the setup, participants, analysis steps and rules, coding, classification and categorisation process, and inter-coder reliability approach taken. The outcomes of the full study performed following this methodology will be reported in Chapter 6.

6. Gesture study and resulting vocabulary (consensus set)

This chapter reports the results of the gesture study and its outcome, the vocabulary of hand gestures for conceptual design. Parts of this chapter have been published in a journal paper[6].

Study including 44 participants was performed to elicit natural and intuitive user defined gestures, following the study methodology detailed in Chapter 5. In total, 1785 gestures were collected, 1083 for Part 1 and 702 for Part 2 of the study, described in Section 5.3.1. Gestures performed during Part 1 and Part 2 of the study were analysed: identified, described in writing, sketched, coded based on the taxonomy used, categorised based on hand form and the path travelled and variants identified, and then statistically analysed to ascertain agreement rates between the participants. Following the analysis, the most frequently used and statistically significant gestures formed the vocabulary of gestures for conceptual design or a consensus set, a set of gestures agreed between the participants.

As discussed in Section 4.3.3, due to gestures being proposed by participants and subsequent inability to determine the required number of participants by performing an a priory power calculation, a decision was made to collect data until saturation was reached. Saturation would be reached when no new gestures were proposed by

[6] Vuletic, T, Duffy, A, Hay, L, McTeague, C, Campbell, G & Grealy, M, 'A novel user-based gesture vocabulary for conceptual design', *International Journal of Human Computer Studies.*

participants i.e. all the gestures the last participant has performed have already been proposed by at least one of the prior participants.

Part 1 of the study had predefined activities, while Part 2 allowed participants to perform any activities they believed would result in the outcome they were supposed to achieve. Additionally, in the Part 2 the outcomes participants were asked to achieve i.e. the objects they were asked to create, varied between the participants, as described in Section 5.3.1. This meant that during the Part 2, participants might perform different activities in order to achieve the same goal, even when they were assigned the same objects, and the gestures performed would potentially not be comparable. Hence, the gesture repetition was tracked for Part 1 and Part 2 separately, as it was anticipated that there might be differences in gesture repetition trends between the two parts of the study i.e. Part 2 was far less likely to reach saturation as new activities could always appear that would lead to performance of new gestures. Part 1 was used as an indicator for the saturation of data.

Number of new gestures proposed by each new participant in both parts of the study was illustrated in Figure 6-1. Bars illustrate the number of new gestures proposed by the participant. Trend lines average these values with a 10 participant moving average. For Part 1 saturation was reached when Participant 29 completed the study. The number of new gestures proposed for Part 2 dropped to two gestures by Participant 29. Although this would indicate saturation, due to the setup of the study and the lack of limitations in terms of what gestures participants could propose, data collection was continued in order to test the trend. While some new gestures did appear beyond Participant 29, the number of new gestures maintained the decreasing trend. While there were some outliers, for both parts of the study the number of new gestures proposed remained at around five new gestures per participant. This combined with the saturation reached at Participant 29 was taken as an indication that no new significant developments were being identified, and data collection was stopped when Participant 44 completed the study.

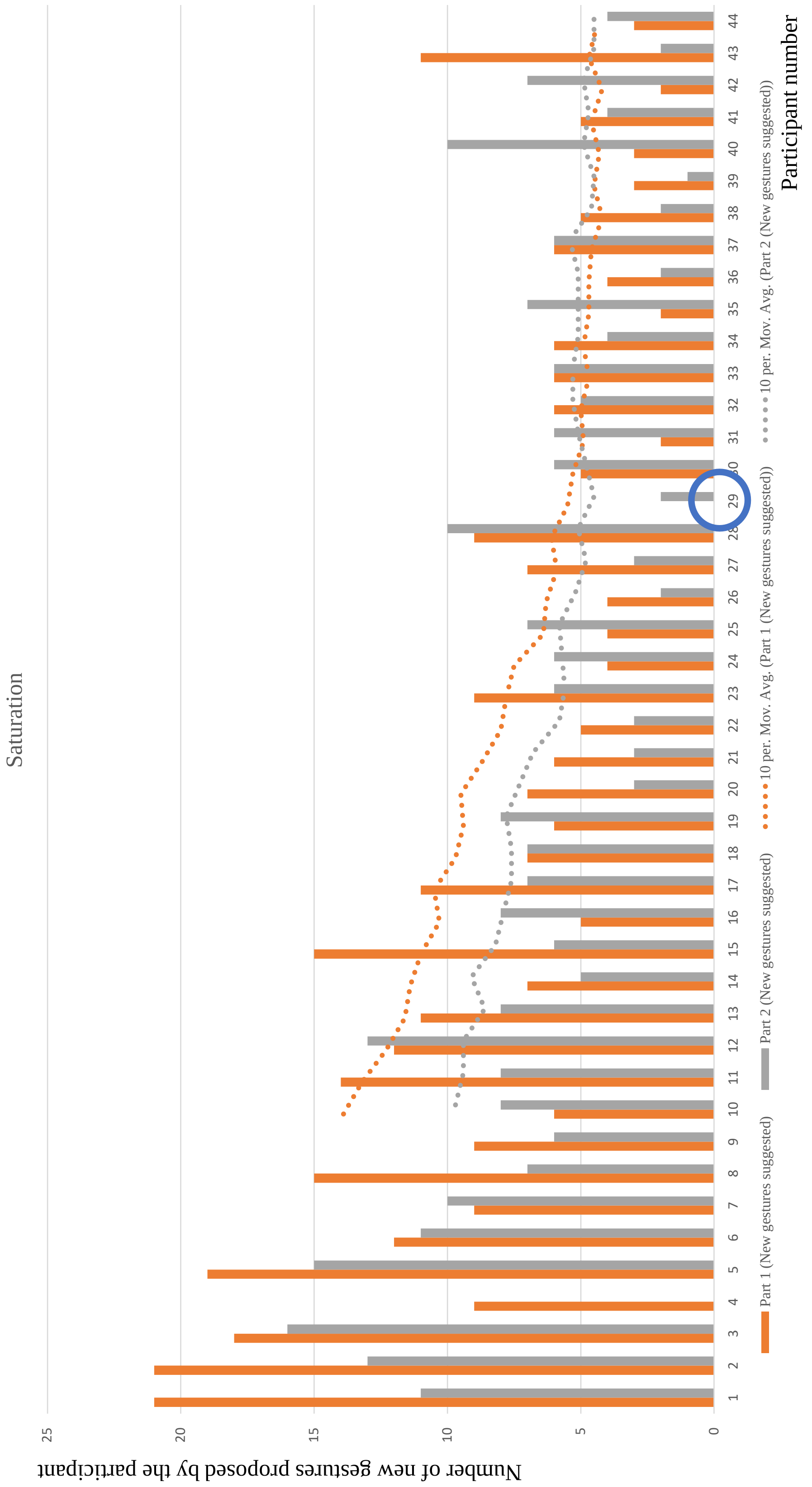


Figure 6-1 : Data saturation for Part 1 and Part 2 of the study

6.1. Gesture parsing

Part 1 of the experiment had 14 unique referents, however counting the *translate, rotate* and *zoom* activities that were repeated multiple times for different objects, this number rose to 25 unique referents. *Zoom in/out*, *Rotate clockwise/counter clockwise*, and *Translate up/down/left right* were repeated for the irregular sphere and the phone, and *Zoom in*, *Translate up*, and *Rotate clockwise* were also repeated for the chair. In Part 1, 1100 gestures were attempted to be collected, but a total of 1083 gestures were successfully performed by the participants and collected for Part 1.

Cameras used for recording did not give any indication of the battery status, and have at two occasions failed to record parts of the study without it being noticed by the author until the analysis was performed the following week. This meant that gestures performed in Part 1 for the last four gestures for Participant four, and the last seven gestures for Participant 20, and Part 2 for Participant four were not recorded. In Part 2 participants had more freedom to determine the activities they would perform, and this meant that the number of gestures they performed was variable with 702 gestures recorded. Six gestures in Part 1 were omitted e.g. participants did not understand what happened on the screen when a surface was deselected and did not perform a gesture with their hands. For four gestures in Part 2 participants performed the same gesture twice with minor variations and in these cases only the first gesture was retained. One gesture in Part 1 was eliminated from the analysis, as the gesture performed was not a hand gesture i.e. participant moved their head closer to the object to zoom in. This left 1785 gestures for the analysis.

6.2. Gesture coding and taxonomy

The taxonomy used for gesture coding, described in Chapter 5 was extended from Wobbrock et al. (2009) and Piumsomboon et al. (2013) and is summarised in Table 6-1. The order of the rows in the taxonomy was adopted from (Wobbrock et al., 2009) to make potential future comparisons of findings easier.

Table 6-1 : Summary of the taxonomy of the gesture coding

Classification type	Sub-classes
Form	Static pose Dynamic pose Static pose and path Dynamic pose and path
Nature	Pantomimic (physical) Metaphorical pantomimic Iconic
Binding	Object-centric (location defined wrt object features), World-dependent (location defined wrt world features), World-independent (location can ignore world features), and Mixed dependencies (world-independent plus another).
Flow	Discrete Continuous
Symmetry	Unimanual, Bimanual symmetric mirrored, Bimanual symmetric copied, Bimanual asymmetric.
Locale	On the surface In-air
Connecting gestures	Hands remain in previous position Hands resting on the table Open palms vertical in air
Dimensionality	2D 3D

For gestures where higher level of interpretation was required; form, nature and dimensionality; three coders were involved in the coding process, to ensure that a consensus was reached among the coders. Three coders coded 10% of the sample (180 gestures). Either 50 units or 10% of the sample is considered an appropriate size of the sample (Lombard et al., 2002). Inter-coder reliability was calculated using Krippendorff's Alpha reliability estimate, and justification for this decision was given in Section 5.3.8.

For the form, Krippendorff's Alpha reliability estimate of 0.8158 was calculated, for the nature of gestures 0.7458, and for the dimensionality 0.8468. Agreement of $\alpha \geq 0.8$ is customarily required, with values of $\alpha \geq 0.667$ the lowest required value where tentative conclusions are acceptable (Krippendorff, 2004a). This meant that for the form and dimensionality the agreement was at a reliable level, whereas for the nature of gestures, it fell slightly short of the required value, but it was still above the lowest required values for tentative results. Due to the discrepancies between the gesture definitions and their applicability to gestures for design (discussed in Section 3.6.3) this was considered acceptable, particularly since the nature of the gestures did not play a crucial role in the gesture categorisation primarily used to form the consensus set (reported in Section 6.3).. At this point, the focus was on the identification of gestures and the reliability and significance of the repetition of gestures between and within the participants, rather than the analysis of the meaning or reasoning behind their use. The coding of gestures in terms of their nature was still performed as it may provide data that could be used in future work, and in order to have data comparable with user elicited gesture research in different but related fields e.g. gestures for surface based devices.

In terms of **form**, vast majority of gestures were in the form of static pose and path, 1711 gestures, or 96% of the performed gestures. Examples of static pose and path are shown in Figure 6-2e and f.

Gestures using dynamic pose were performed by only thirteen participants. Some examples of the activities were: snapping their fingers to indicate beginning of a new sketch, thumb and index finger moving further apart to create a handle on a cup (fill activity, shown in Figure 6-2c) and the same activity to create a rectangular sketch on a surface (draw activity), or thumb moving away from the rest of the hand to extrude a sketch shown in Figure 6-2d. These were all different and seemed to indicate a personal preference and did not correspond to the size of the object.

Static pose was used by eleven different participants. They held one or both hands still to indicate creation of a shape (cylinder, cup handle or an extruded rectangle shown in Figure 6-2a and b), held a hand to select a shape, held a hand to select a plane, held both hands with fingers pointing at each other to indicate the space between them would be filled by some shape (loft activity), held a hand as it was holding a sphere in order to create a sphere, or held both hands facing each other in a vertical plane to indicate rotation. On their own, these static gestures would not be able to convey the activity unless they were predefined and linked to a specific activity prior to use.

Gestures using dynamic pose and path were performed by eleven participants. They were used to extrude (shown in Figure 6-2g), zoom in or out (shown in Figure 6-2h), undo an activity, draw a triangle, or extrude cut a shape, and were generally similar to the static pose and path gestures performed for the same activities, except the moving hand changing shape provided more indication of what the activity is e.g. for zoom in fingers of the moving hand move apart to indicate increase of size of the object being zoomed into. Activities other than zoom in or out were only performed using these type of gestures in the second part of the study, where participants were free to propose their own activities.

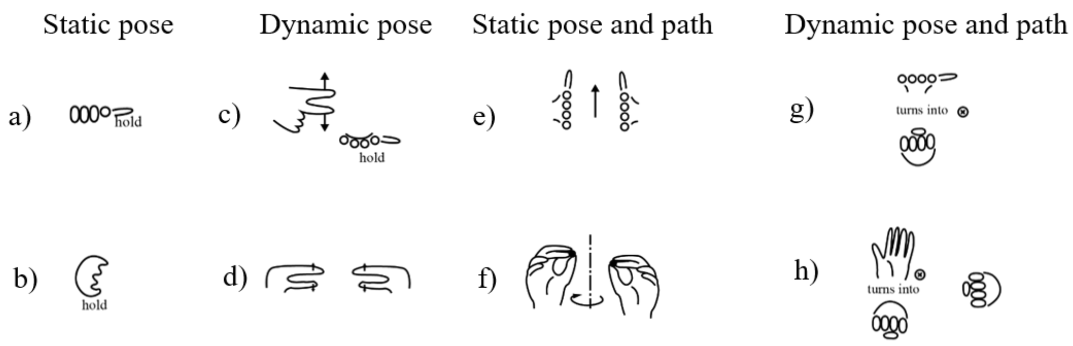


Figure 6-2 : Examples of form

Observing the **nature** of the gestures, over 70% of gestures performed were iconic. These gestures would be required to be learnt prior to use. Although they often resembled physical gestures that would have been used to manipulate the object, they were lacking some elements or information that would have fully described the activity performed without prior knowledge of the goal of the activity. Less than 30% of the gestures performed were pantomimic i.e. emulated interaction with an object as if it was a physical interaction that would have taken place with a physical object. Three gestures were metaphoric pantomimic gestures, where full pantomime of an activity was performed, but the activity pantomime was emulating had a different goal than the activity shown in the video. To *zoom in* two participants had “pulled a rope”, and to raise the height of an extruded surface a participant had “poured water” into it. Examples for all three types of nature classification were detailed in Chapter 5 Section 5.3.4.1.2. The visual representation of frequency of different gestures appearing in the data is given in Figure 6-3, for all 8 taxonomy classes.

Classification based on **binding** criteria showed that all gestures were object-centric. This was determined by the study design, it was explicitly asked of the participants, and one instance of the gesture where viewpoint was changed instead of performing the gesture to zoom was already eliminated from the sample prior to the analysis. Similarly, study design, which required participants to perform gestures as if they were controlling the activity shown on the screen while it was happening, meant that for Part 1 of the study in terms of **flow** gestures were continuous by design. In Part 2 participants were not instructed to perform continuous gestures, but due to the nature of the activities, they were all continuous. Participants created a 3D part starting with the empty space in front of them, and finishing with an imaginary 3D model suspended in the space in front of them, going through a number of steps. Each step contributed to a creation of a piece of the geometry and imagining it was appearing as the gesture progressed, naturally corresponded better to the continuous gestures than discrete gestures.

The split between unimanual and bimanual gestures was close to equal, with unimanual gestures counting for 47.8% of the performed gestures. Bimanual asymmetric gestures were 19.4% of the total sample, bimanual symmetric mirrored gestures were 32.4% of the total sample, and only 7 gestures (0.4% of the sample) were bimanual symmetric copied gestures. Some unimanual and bimanual gestures were identical, with the difference that for the bimanual gestures the additional hand was used to hold the object being modified in place. In this study they were classified as different gestures, however in the future work, when the vocabulary reaches the implementation stage these gestures may merge into a single gesture. At that point, a decision would have to be made if it is required to hold the object in place, or if it would be assumed that the object is stationary unless indicated otherwise.

Figure 6-3 : Gestures coded by form, nature, binding flow, symmetry, locale, connecting gestures and dimensionality

In terms of **locale**, the majority of gestures, 96%, were performed in-air. As participants were sitting at a table, some used the table to rest one of their hands while performing the gestures. However, as the other hand would still have been used in-air, although the resting hand would not have been in-air, these gestures were still classified as in-air. Gestures were classified as on the surface if they were in contact with the table for the entirety of the activity. For example, a gesture used to perform translate left activity shown in TL06 slid the hand to the left along the table, and it was classified as on the surface, as shown in the image on the left in Figure 6-4 (as described in Section 5.3.4 gestures were described adopting the participant's point of view). Gesture used to pattern a shape around, MulPat07, in some instances touched the table, however the motion "moving" the shape to the next position was fully in-air, conveying a key element of the activity, and without it the gesture would have been incomplete. Hence, this gesture was classified as in-air, as shown in the image on the right in Figure 6-4.

Figure 6-4 : Example of on surface and in-air classification

Since natural and intuitive gestures were explored with the view of eventually contributing to a language for conceptual design, it was important to explore what the **connecting gestures** were, or what the transition was between the two consequent gestures. This category was not predefined, but instead identified from the recordings for the Pilot study 2 initially, and then Part 2 of the study, where uninterrupted design took place. Only two distinct activities took place in the full study. Hands either remained in the previous position i.e. last position from the gesture that was just performed, while the participant was thinking about the next step (85%), or they were resting on the table (15%). In the Stage 1 of Part 2 of the full study, there were interruptions between the predefined stages and connecting gestures between two stages were not included in the sample. This was because the participants may not have been thinking about the design activities during these interruptions. For the majority of these the hands were resting on the table (92%).

Observing **dimensionality** for the participants who stated they did not perceive the objects as 3D (Participant 12, Participant 25, and Participant 33) or did not know if they perceived them as 3D (Participant 16), it was found that 90% of the gestures were performed as if the object was perceived in 3D. The majority of 2D gestures were used for translation, perhaps emulating the tablet interaction paradigms. These gestures are shown in Figure 6-5.

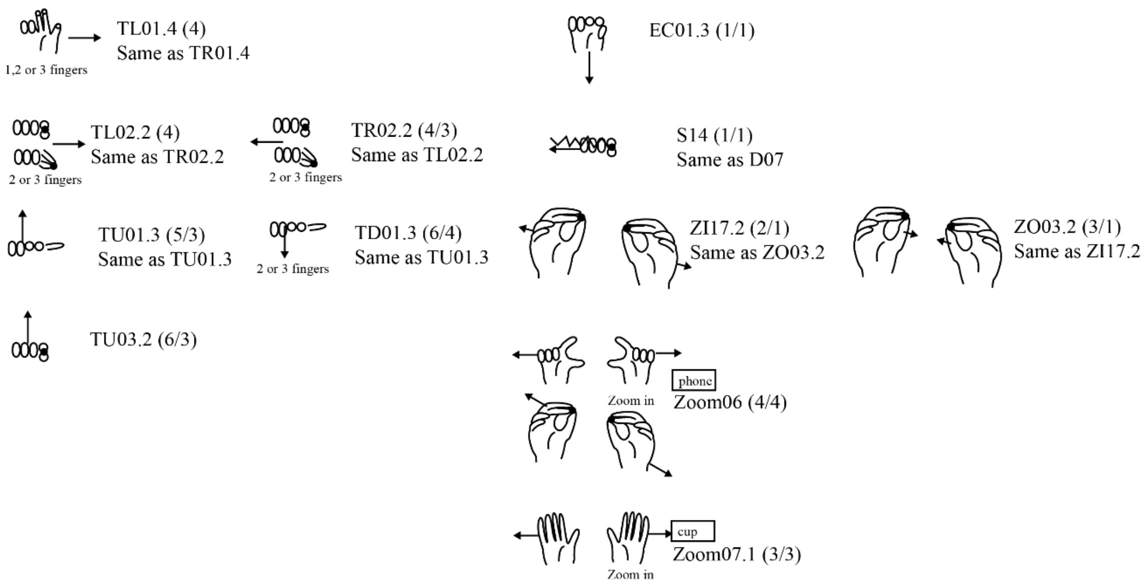


Figure 6-5 : Gestures participants stating they did not perceive objects as 3D performed in 2D

6.3. Gesture categorisation

Once gestures were parsed, sketched and coded, they were categorised based on similarity, and assigned unique identifiers. Very limited interpretation had taken place during the categorisation. Gestures were categorised based on the paths the hands travelled (or for static pose stationary poses), and variants within each category were identified based on the form the hand took. If the object was “held” by at least one hand was considered as well. However, the gestures were still described by the coder(s), instead of coordinates of the tracked hands being registered by a motion capture system for example. Hence, limited interpretation did at times take place as magnitude of the motion or exact trajectory were not noted. Detailed description of the categorisation process is given in Chapter 5, section 5.3.4.2, along with the Figure 5-13 exemplifying the categories and variants for *Translate Left* activity. Outcomes of the categorisation, both sketches of gesture categories and variants, can be seen in in the Appendix G, Section G3 and G5. The table containing the descriptions of gestures is provided in the supplementary data.

Agreement rate (AgR) was calculated for each of the activities and the categories within it using a calculation derived by Findlater et al. (2012) and adopted by Vatavu and Wobbrock (2015). Agreement rates for Part 1 and Part 2 of the study can be seen in Figure 6-6 and Figure 6-7, respectively. AR rate measures the homogeneity for nominal data.

The formula for the AgR is:

$$AgR_i = \sum_{k=1}^{q} \frac{n_{ik}(n_{ik} - 1)}{n_i(n_i - 1)}$$

Where q is the total number of gestures produced by the gesture classification process, n_{ik} is the number of occurrences of a gesture G_k for referent R_i and n_i is the total number of gesture proposals for referent R_i.

Guidance for the interpretation of calculated values is given in Table 6-2.

Table 6-2 : AR results interpretation

AR	Interpretation
<=0.1	low agreement
0.1-0.3	medium agreement
0.3-0.5	high agreement
>0.5	very high agreement

Agreement rates below 0.1 require further data collection. Agreement rates between 0.1 and 0.3 indicate medium agreement. Rates between 0.3 and 0.5 indicate high agreement, and AgR above 0.5 indicates a very high agreement.

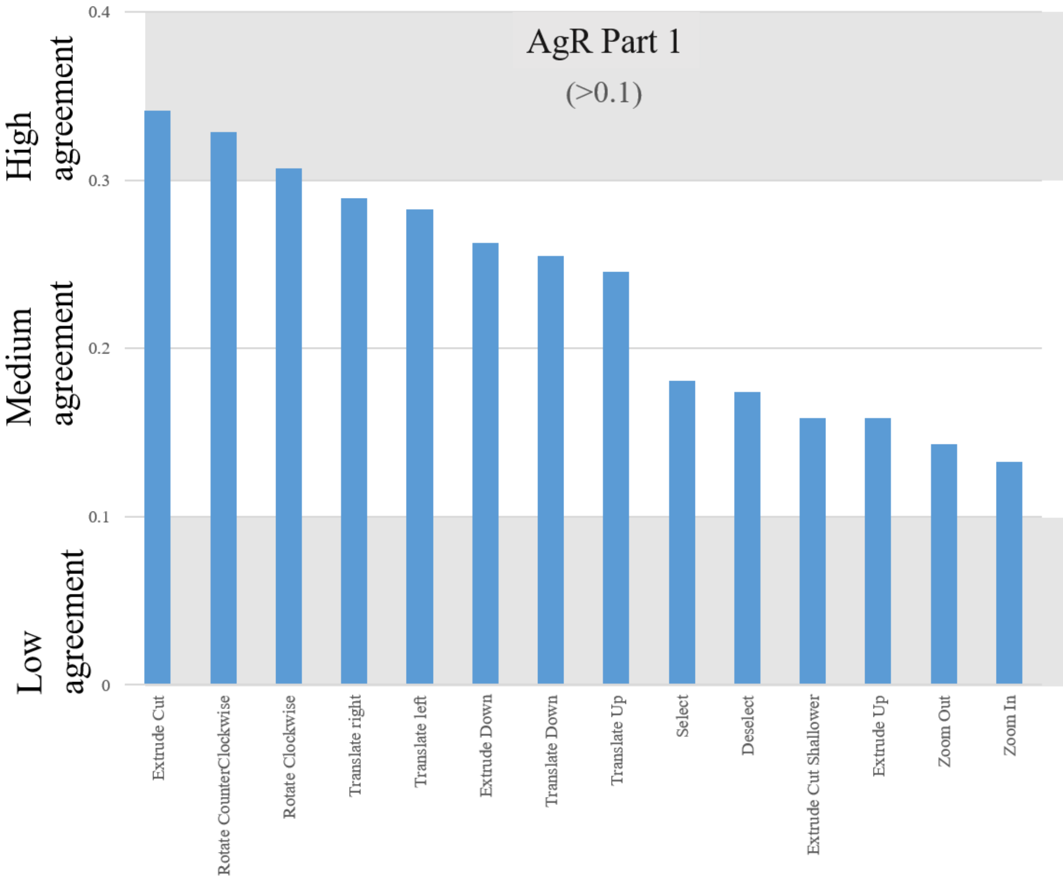


Figure 6-6 : Agreement Rates for Part 1

For the Part 1 all agreement rates were above 0.1, indicating at least medium agreement. AgR for *Rotate clockwise*, *Rotate counter clockwise* and *Extrude cut* were above 0.3, indicating high agreement.

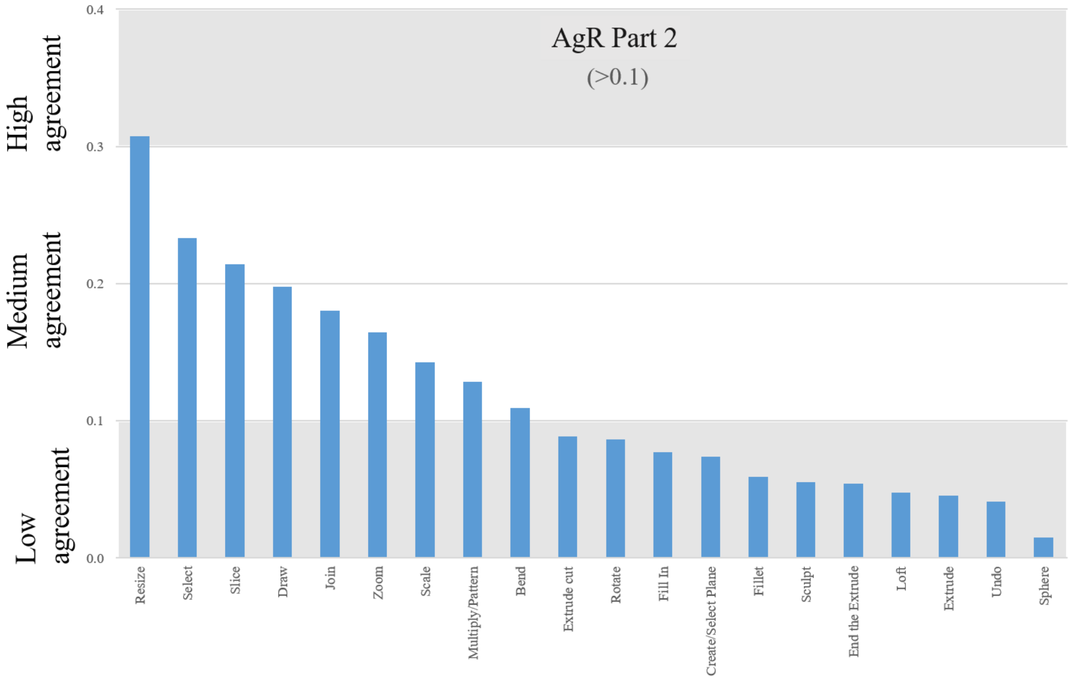


Figure 6-7 : Agreement Rates for Part 2

For the Part 2, AgR for 11 activities indicated low agreement, and AgR for nine activities were above 0.1, indicating at least medium agreement. AgR for *Resize* was above 0.3, indicating high agreement.

Agreement Rate is widely used, but not universally accepted as a measurement for selection of appropriate gestures for the inclusion in the consensus set. Tsandilas (2018) suggests that an additional measure should be used to chance-correct the coefficients and specific agreement i.e. ensure that agreement did not happen by chance. Use of Fleiss'κ or Krippendorfsf's α is suggested by Tsandilas.

In this study, Fleiss' κ was calculated to correct for chance of agreement:

$$\kappa = \frac{p_a - p_e}{1 - p_e}$$

Where:

$$p_e = \sum_{k=1}^{q} \pi_k^2, \;\; \pi_k = \frac{1}{m} \sum_{i=1}^{m} \frac{n_{ik}}{n_i};$$

m is the total number of items, n_{ik} is the number of gestures per item i having category k, and n_i is the total number of gestures for item i.

Guidance for the interpretation of the results is given in Table 6-3.

Table 6-3 : Fleiss' kappa results interpretation

κ	Interpretation
< 0	Poor agreement
0.01 – 0.20	Slight agreement
0.21 – 0.40	Fair agreement
0.41 – 0.60	Moderate agreement
0.61 – 0.80	Substantial agreement
0.81 – 1.00	Almost perfect agreement

In this study fair agreement was required at the minimum e.g. κ>0.21. κ values for different activities are given in Table 6-4.

Table 6-4 : AR, Fleiss' kappa values for activities in Part 1 and Part 2 of the study

Part 1 Part 2

Gesture	AR (>0.1)	Fleiss κ		Gesture	AR (>0.1)	Fleiss κ
Extrude Cut	0.341	0.897		Resize	0.308	0.163
Rotate Counter Clockwise	0.328	0.898		Select	0.233	0.632
Rotate Clockwise	0.307	0.923		Slice	0.214	0.457
Translate left	0.282	0.989		Draw	0.198	0.927
Translate right	0.289	0.971		Join	0.180	0.679
Extrude Down	0.262	0.879		Zoom	0.165	0.35
Translate Down	0.254	0.974		Scale	0.143	-1.021
Translate Up	0.245	0.963		Multiply/Pattern	0.129	0.43
Select	0.180	0.828		Bend	0.110	0.316
Deselect	0.174	0.831		Extrude cut	0.089	0.684
Extrude Cut Shallower	0.158	0.775		Rotate	0.087	0.509
Extrude Up	0.158	0.748		Fill In	0.077	-0.172
Zoom Out	0.142	0.789		Create/Select Plane	0.074	0.605
Zoom In	0.132	0.715		Fillet	0.059	0.016
				Sculpt	0.055	0.059
				End the Extrude	0.055	-1.33
				Loft	0.048	-6
				Extrude	0.046	0.606
				Undo	0.041	0.218
				Sphere	0.015	-3.713

Gestures for an activity were added to the consensus set only if AgR was above 0.1 showing at least medium agreement, and if Fleiss' κ was showing at least fair agreement (>0.21). Tsandilas determined that chance agreement (indicated by Fleiss' κ here) was not a major issue for studies where "(i) participants choose from a large space of gestures, (ii) their proposals discriminate between many of these gestures with low bias, and (iii) the gesture classification process differentiates between subtle gesture variations". Additionally, studies focusing on direct manipulation gestures had lower problem of chance agreement, as continuous nature of gestures and spatial limitations "made bias and conflict between different referents" less likely to occur. He also stated that it is always safer to report chance-corrected agreement indicators, as this is the practice in many other fields that could be adopted in gesture elicitation studies.

Some researchers recognised that numerical thresholds determining agreement were arbitrary. For example, Krippendorff (2004b) suggested the threshold levels should be chosen depending on the "costs of drawing invalid conclusions form the data". This gesture elicitation study had a theoretically unlimited space of gestures, proposals discriminated between the gestures without bias (as participants were not aware of other participants' proposals and the coders did not interpret the gestures and aligned them to predefined symbols), and the gesture classification process did differentiate between gesture variations. Due to the early stage of this research, unlimited space of gestures and methodological approaches taken to analysing them, it was determined that lower limits for gesture inclusion, medium agreement for AgR and fair agreement for Fleiss' κ were appropriate. This would ensure that gestures were not eliminated from the vocabulary prematurely.

All activities performed in the Part 1 had representatives in the consensus set. In Part 2 only eight activities had both AgR and Fleiss' κ that were higher than the required value: *Resize*, *Select*, *Slice*, *Draw*, *Join*, *Zoom*, *Multiply/Pattern* and *Bend*.

Translate Left will be used in this paragraph to illustrate how the specific categories were included. All gestures categorised and split into variants were given in the Appendix G, Section G.5. It was noticeable that some variants for the categories were appearing much more frequently, and the top four or five were marked with a blue background. At this point, no gesture variants were eliminated; the variants with higher repetition were just highlighted. AR and Fleiss' κ determine which gesture categories had most agreement, but did not explore which gestures within them should be included in the consensus set. That is why they were supplemented by Chi-Square goodness of fit test, detailed in the following section. However, at this stage of consensus set building process any variant that had at least four repetitions was included, as that meant at least 10% of the participants have repeated those gestures. At this point, this value had no statistical significance, and would be further tested by the Chi-Square goodness of fit test. Looking at different activities, number of repetitions that was higher than the average varied. For some activities, gestures were repeated in the order of magnitude of 20. For others four repetitions were substantially higher that one or two repetitions that occurred for the remaining categories and variants. For some activities, only two or three variants fit this criterion. *Translate up* had six variants that were noticeably more repeated than others, and it was the only activity where six variants were included.

Following the AgR and Fleiss kappa analysis, consensus sets for both parts of the study are given in Figure 6-9 and Figure 6-10. Gestures which were repeated by more than 10% of participants, but where the entire category was excluded from the consensus set as either AgR or Fleiss Kappa were too low to justify the inclusion are given in Figure 6-11. Sketches used to illustrate the gestures followed the gesture representation framework developed by McAweeney et al. (2018), further modified for the needs of this study. The framework is illustrated in Figure 6-8.

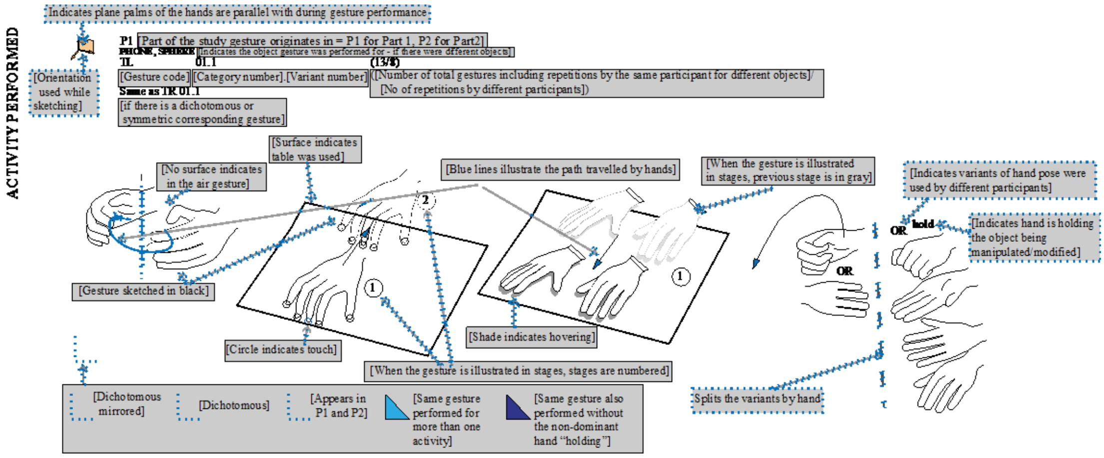


Figure 6-8 : Framework for gesture sketches

As the Figure 6-8 shows, gestures were represented in the isometric view. Above the gesture, text indicated which part of the study the gesture appeared in, which objects it was used for, what the gesture code, category and variant number were, and how many repetitions occurred including the repetitions by the same participant for different objects and number of repetitions by different participants only. Where the gestures had more than one sequence, the sequence stages were numbered. In-air gestures were shown without a surface below them. Where the table was used surface was represented. If the table was touched this was indicated with blue circled touchpoints. When the hand was hovering over the surface of the table shadow was added to indicate this. Motion paths were indicated by blue arrows and paths. Coordinate system in the top left corner indicated the directions of the axis and planes of the space the isometric view was set in, and highlighted planes indicated parallelism with the palms of the hands shown in the specific gesture sketches. Where multiple positions were shown in one sequence stage, previous position was shown in grey. Symbol placed at the bottom left of each gesture, if present, indicated that the specific gesture either had a dichotomous mirrored counterpart in the vocabulary (yellow symbol), dichotomous counterpart (orange symbol), activity appeared in both parts of the full study but gesture appeared in Part 2 only (green symbol), same gesture was performed for more than one activity (light blue symbol) or the same gesture was also performed using the non-dominant hand to "hold" the object (dark blue symbol). Examples of this are given in the discussion following Figure 6-11.

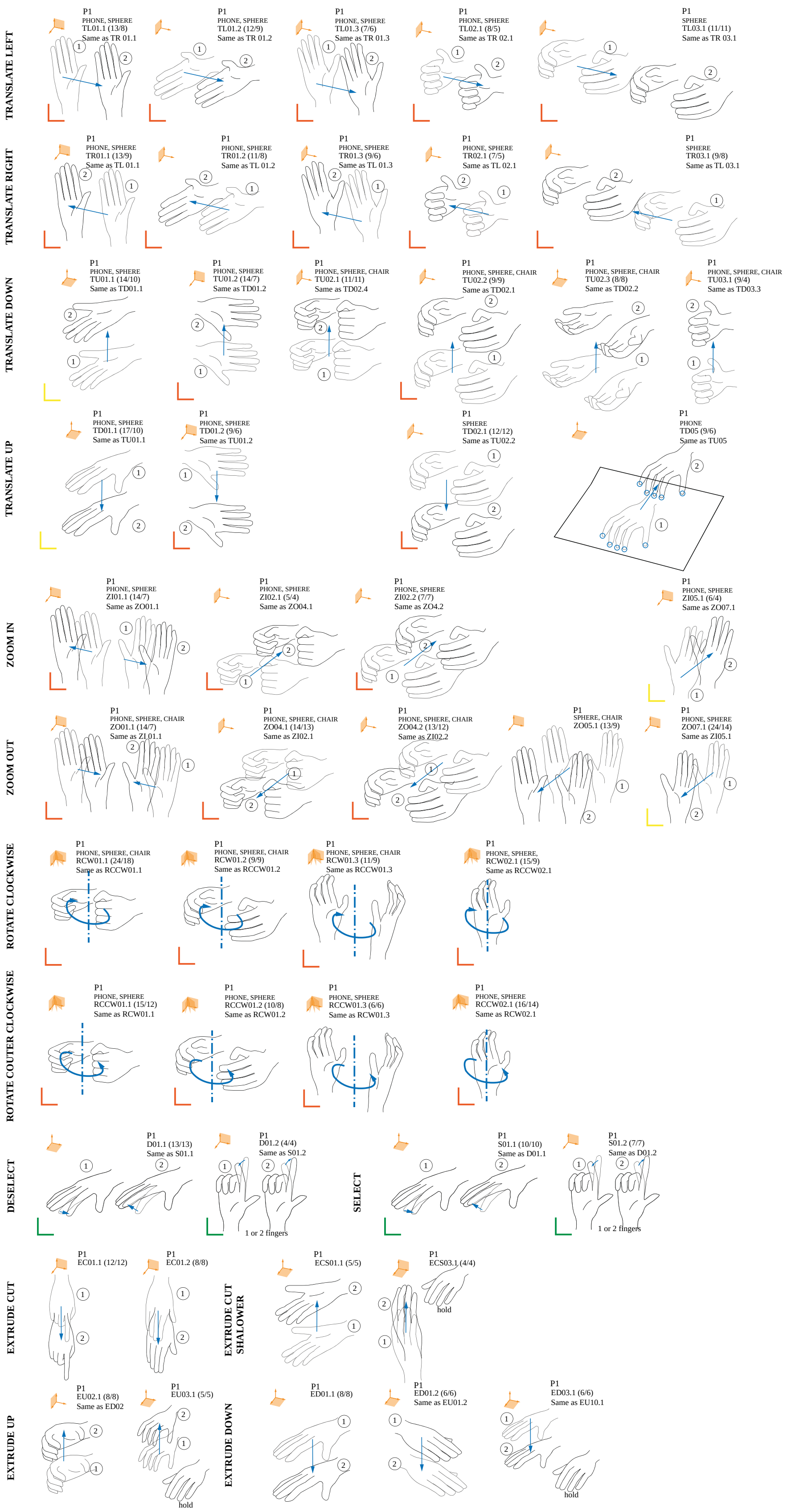


Figure 6-9 : Consensus set for Part 1

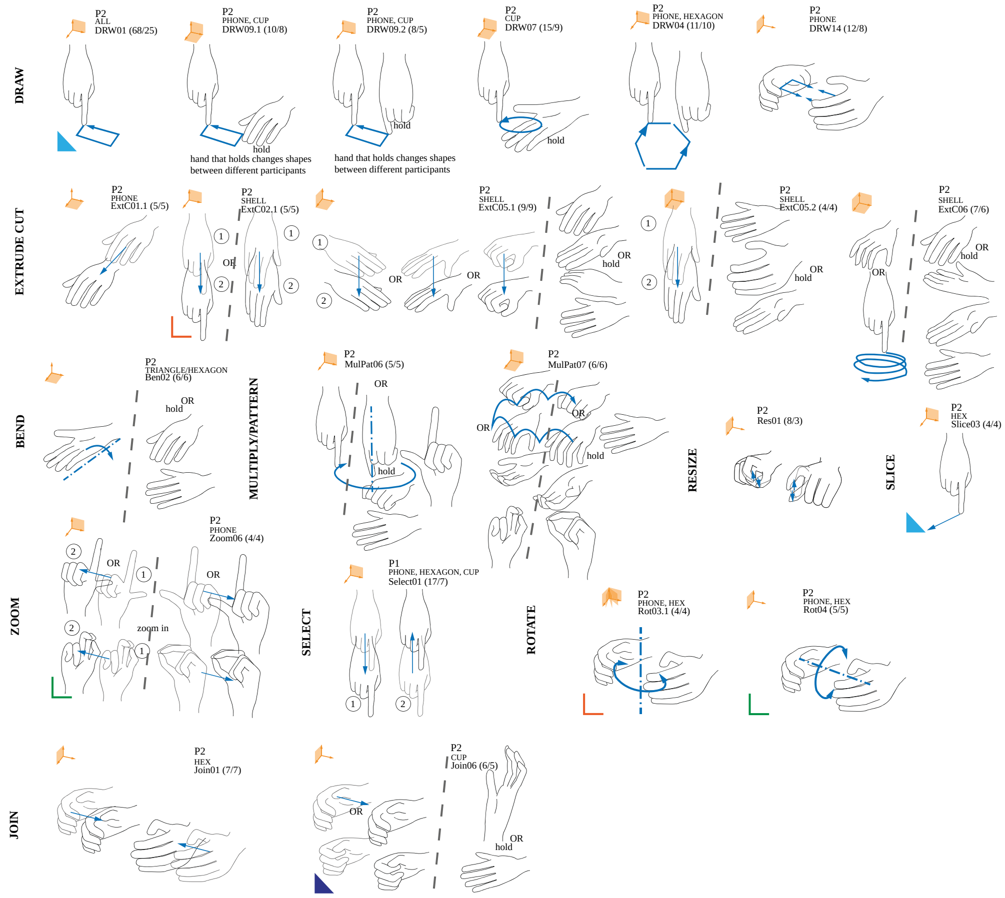


Figure 6-10 : Consensus set for Part 2

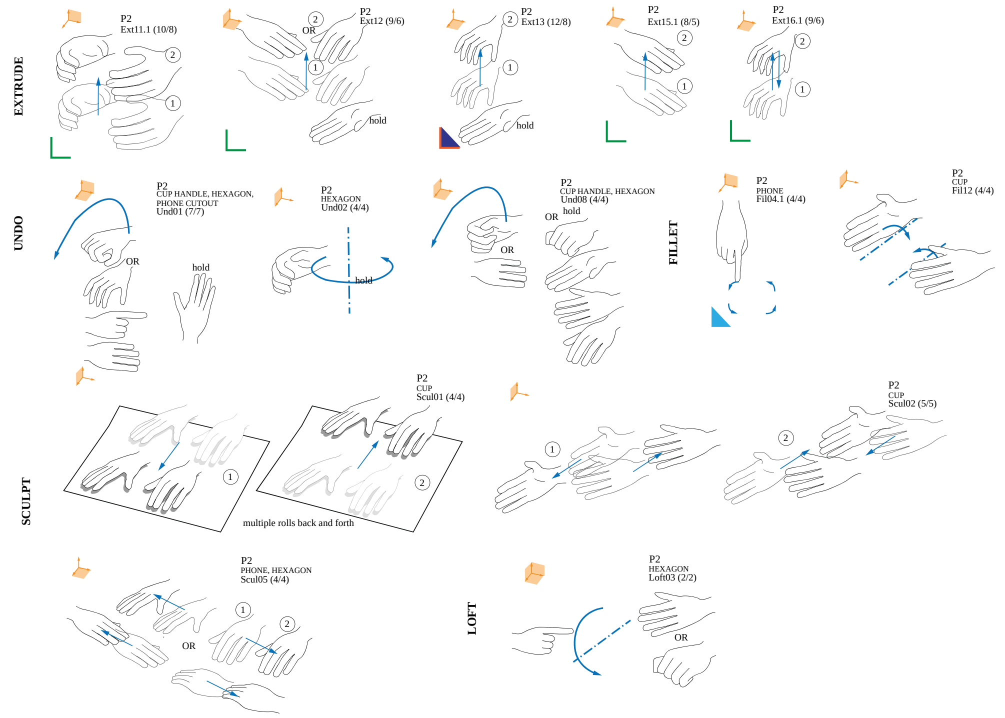


Figure 6-11 : Excluded set (to be reviewed following gesture evaluation)

During the coding, it was noticed that gestures for *Bend*, *Sculpt*, *Multiply/Pattern*, *Loft* and *Undo* depended highly on the shape of the object being manipulated. For example, *Undo* was occasionally performed using a symbolic gesture that did not take into account the shape of the object, such as emulating throwing the object away or "erasing" it by moving a hand left to right as if using an eraser. However, at times the latest activity e.g. rotating a triangle around an axis to pattern it was performed in reverse. That was, it rotated in the opposite direction, to undo. While the influence of the shape of the object on the gesture was established primarily by the existence of the accounting of the shape of the object by the forms and paths the hands take, there was some justification of this shown in the number of shared gestures suggested for different shapes of the object for the same activity. Out of 26 suggested gestures for *Undo* activity, only three were suggested for more than one shape/object. For *Bend* out of 11 suggested gestures, only three were suggested for both shapes it was applied to. For *Sculpt* out of 18 only one gesture was suggested for more than one shape/object. *Multiply/pattern* and *Loft* activity gestures were mostly suggested for a hexagon only. This raised the question if the data collection for the shape dependent activities needed to be different, or if shape dependence was desirable and the larger sample should be collected so that the specific shapes could be analysed independently in the future.

Gestures that were consistent across the dichotomous activities, e.g. for TL01.1 and TR01.1 where the hand formed the same shape and followed the same path, just in different directions as it was translating left or right, were marked with an orange symbol. Gestures that were symmetric across the dichotomous gestures, e.g. TU01.1 and TUD01.1 where the hand formed a mirrored image and moved along the same path but in opposite directions, were marked with the yellow symbol. Gestures that appeared in Part 2 only for the activity that existed in Part 1 were marked with the green symbol.

Dichotomous gestures showed a high degree of consistency, used reversible gestures, and in some cases there was a degree of symmetry e.g. mirroring the hand pose for the similar activity but a different direction.

Occasionally, same gestures were performed to achieve different activities. For example, Ext 13 and a variant of Join 06 performed the same gesture, although in different orientation, resulting in a different outcome. The same hand pose and style of motion with free path was used for Drw 01, Fil 04.1 and Slice 03 activity. Some of them were eliminated from the consensus set due to lack of agreement of statistical significance. However *Draw* and *Slice* conflict remained. If the gestures were to be implemented in a solution used for conceptual design, a decision would have to be made on how to resolve this conflict.

It was also noticeable that sometimes one or two hands were used in gestures performed for the same activity, where the hand actually performing the nominal activity was performing the same gesture, while in the bimanual variants the additional hand was used to hold the object or a part of the object being modified or manipulated in place. Good examples of this are ED01.1 and ED 03.1 in Figure 6-9. At this stage, both variants were retained in the consensus set. Depending on the recognition methods used for gesture implementation in the future, some of these gestures may become obsolete e.g. if it is decided that an object does not need to be held.

6.4. User defined set of gestures

AgR and Fleiss'κ indicated if there was sufficient agreement between the participants proposing gestures from a theoretically infinite set of gestures, and if the agreement was statistically significant, respectively. They however did not determine what number of repetitions for a specific gesture was required for the gesture to be included in the consensus set. To determine this, Chi square Goodness of Fit analysis was performed to determine if the number of repetitions for different categories within each activity was likely to happen by chance (Cochran, 1952), and what number of repetitions was expected for each category. Calculations used for the Chi square Goodness of Fit analysis were the same as the ones used in the Pilot study (given in Appendix B, Section B 1.5.3:

$$X^2 = \sum \frac{(O-E)^2}{E};$$

Where X^2 is Chi-Square goodness of fit test, O – observed frequency, E – expected frequency.

The calculations were performed using SPSS and the results for all gestures can be seen in the supplementary data. Chi-Square goodness of fit was calculated for one shape at a time where gestures were performed for a number of different shapes.

The consensus set was then further refined by adding information from the Chi-Square analysis. Gestures where number of repetitions for a category of gestures was lower than what would have happened by chance were removed from the consensus set. Values for different activities and objects interacted with in Part 1 of the study can be found in Table 6-5. While all p values were significantly lower than the Bonferroni corrected p value, indicating that the repetition of gestures was unlikely to happen by chance, for a number of gestures the expected number of repetitions was lower than five, meaning that Chi-Square could not provide definitive conclusions. These cases were recalculated using the Exact test of goodness of fit, and those values were reported instead. In it, instead of calculating a test statistic that measures how different the findings were from the expected values and then calculating the probability of this event, p value was calculated directly. Calculations were performed using SPSS. Values for different activities and objects interacted with in Part 2 of the study can be found in Table 6-6.

Since Part 2 did not have a controlled number of repetitions, i.e. participants largely chose their own activities during object creation, for the majority of the gestures and objects the number of expected repetitions was not high enough (for 18 out of 20 gesture types). Additionally, the number of participants that performed specific gestures varied. Only two gestures were shown to have happened more frequently than expected. These were *Draw* and *Select* and they were added to the main consensus set. The remainder of gestures were retained for descriptive purposes in a separate set. This meant that the repetitions for consensus set for Part 2 could have happened by chance.

Table 6-5 : Chi-Square results for Part 1 of the study

Gesture	Bonferroni corrected p value	Chi Sq Phone	Chi Sq Sphere	Chi Sq Chair	Chi Sq Console	Expected number of repetitions
Extrude Cut	0.050				**6.054E-12**	6.1
Rotate CounterClockwise	0.025	**6.455E-06**	**7.943E-09**			8.8; 7.0
Rotate Clockwise	0.017	**4.690E-06**	**9.536E-08**	**1.527E-07**		8.8; 6.1; 8.6
Translate left	0.025	**2.416E-12**	**3.640E-05**			6.1; 7.3
Translate right	0.025	**1.051E-12**	**3.177E-05**			6.3; 7.2
Extrude Down	0.050				**3.406E-09**	5.4
Translate Down	0.025	**9.444E-10**	**1.074E-07**			5.5;6.3
Translate Up	0.017	**1.817E-06**	**7.695E-09**	**9.574E-09**		6.1; 5.8; 5.5
Select*	0.050				**8.552E-14**	2.6
Deselect*	0.050				**2.662E-11**	2.8
Extrude Cut Shallower*	0.050				**1.056E-05**	3.9
Extrude Up*	0.050				**1.087E-04**	4.3
Zoom Out*	0.017	**5.407E-05**	**4.732E-05**	**7.316E-06**		3.3; 3.4;4.4
Zoom In*	0.025	**3.362E-07**	**2.449E-06**			2.8; 2.9

Table 6-6 : Chi-Square results for Part 2 of the study

Gesture	Bonferroni corrected p value	Phone	Phone-shell	Phone-mic	Cup	Hexagon	Hex-Hex	Hex-Tri	Hex-Square	Hex-bend tri	Hex-bend hex	Hex-pattern with rot	Hex-copy	Hex-undo pat	Hex-undo square	Sphere	Expected number of repetitions
Resize	0.010	**4.463E-02**															1.8;
Select	0.017	**9.569E-01**			**1.036E-02**	**1.084E-02**											1.9;2;2.2
Slice	0.017					**3.425E-01**											1.6
Draw	0.017	**1.112E-04**			**2.457E-31**		**9.555E-03**	**1.005E-02**	**1.412E-01**								3.6; 4.7;3.1;3.3
Join	0.017				**4.290E-01**	**2.307E-02**											2.4;4..3
Zoom	0.025	**3.208E-01**			**6.834E-01**												2;1.4
Scale	0.010	**8.964E-01**			**1.000E+00**												1.3;1
Multiply/Pattern	0.025											3.916E-01	4.934E-01				2.3;1.7
Bend	0.017									**7.358E-01**	**9.140E-01**						2.6;1.5
Extrude cut	0.010		**4.666E-01**	**3.745E-02**	**1.755E-01**	**1.755E-01**	**1.755E-01**										2.5;2.3;2.9;2.9
Rotate	0.013	**1.991E-01**			**3.916E-01**	**7.055E-01**											2;2;3.5
Fill In	0.025				**6.817E-01**												1.4
Create/Select Plane	0.017	**1.000E+00**			**5.724E-01**	**9.973E-01**											2;2.5;1.4
Fillet	0.017	**8.043E-01**			**4.340E-01**												1.8;2.5
Sculpt	0.025	**Too many different shapes to have statistical significance**															-
End the Extrude	0.013				**9.822E-01**	**1.000E+00**											1.2;1
Loft	0.050					1.000E+00											1
Extrude	0.017	**6.456E-01**			**4.508E-02**		**1.081E-02**	**9.013E-01**	**5.835E-01**								2.1;2.8;1.9;1.4;1.6
Undo	0.050	**9.977E-01**			**7.766E-01**									6.472E-01	8.964E-01		1.1;1.6;1.3;1.3
Sphere	0.025															9.999E-01	1.1

The revised consensus set is shown in Figure 6-12, and the revised excluded set is shown in Figure 6-13.

It was noticeable that some gestures were used only for interaction with the sphere, for example, three out of four *translate* activities used both hands to move the gesture, TL and TR 03.1, and TD 02.1. However, for other activities similar hand shapes using two hands were used for all other shapes too. The majority of other activities were performed for at least two objects of distinctly different shapes. This was considered to be beneficial for the vocabulary being built with the intention of becoming a base vocabulary set for design, as it was assumed they would be applicable to objects of varied other shapes.

While participants have not reported major issues with gesture performance, it should be noted that four participants found *select/deselect* gesture activity hard to understand. Eight participants noted that hexagon creation was more difficult than the rest of the objects, due to its complex shape.

Both the revised consensus set and the revised excluded set would be evaluated by ten participants with varied backgrounds, excluding design, in order to further generalise the vocabulary and reduce the influence of design training study participants have had during their education.

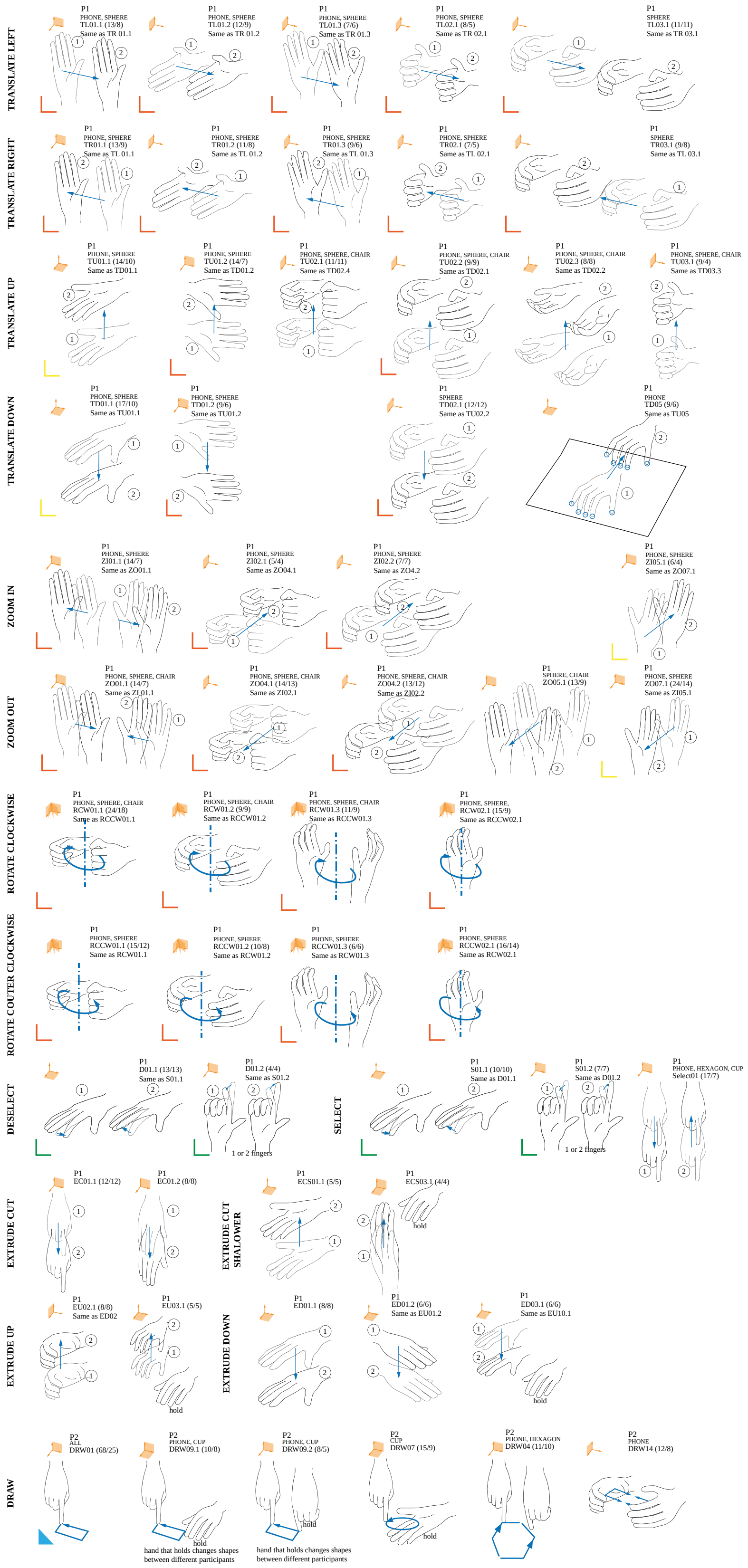


Figure 6-12 : Revised consensus set for Part 1 and Part 2

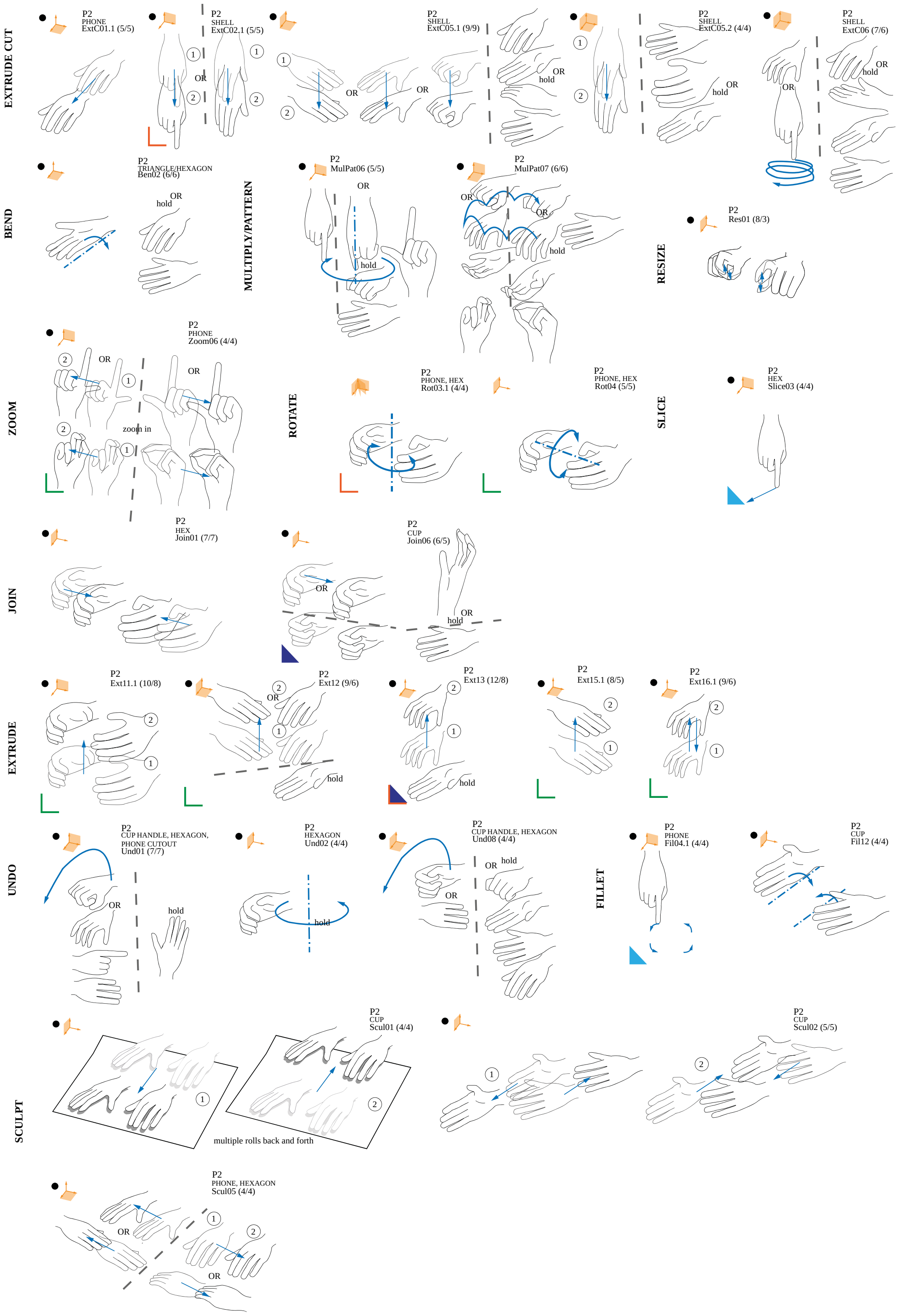


Figure 6-13 : Revised excluded set for Part 1 and Part 2 (to be reviewed following gesture evaluation)

6.5. Summary

A study was performed for gesture elicitation including 44 3rd-5th year Product Design Engineering (PDE) students or graduates at Department for Design Manufacturing and Engineering Management at University of Strathclyde, or the Glasgow School of Art and the School of Engineering and Physical Science at the University of Glasgow. 1792 gestures were added to the data set, 1090 from Part 1 and 702 from Part 2 of the study.

These were then parsed, sketched and coded based on the taxonomy defined in Chapter 5, following the user based gesture elicitation approach established in the field of HCI. Then they were categorised based on the hand form and the path travelled, in a number of categories and sub categories. Statistical analysis including combination of AgR and Fleiss κ was used to determine which gestures should be added to the consensus set for the gesture vocabulary for both parts of the study. Chi square analysis was then applied to the categories of gestures in order to determine the likelihood of number of repetitions for each category occurring by chance. Following Chi square analysis, a number of categories were disqualified from the consensus set, and then the consensus sets for Part 1 and part 2 of the study were merged into a unified consensus set.

This consensus set, shown in Figure 6-12, represents the variants for 20 in-air gestures frequently used during conceptual design, and these are suggested to be used as a base for further development of a vocabulary for conceptual design in 3D space.

The consensus set for a vocabulary for conceptual design, and the set containing gestures excluded at this stage were evaluated and revised following the evaluation approach defined in Chapter 5, Section 5.3.5. This is reported in Chapter 7.

7. Testing and evaluation

A consensus set (gesture vocabulary) for form creation was compiled following the study completion reported in Chapter 6, and presented in Section 6.4. Participants in the study were 3rd-5th year Product Design Engineering students, as they are skilled and experienced enough to provide insight into the needs of designers, but have not fully adopted established ways of working in industry. However, if a vocabulary is to be developed, that is natural and intuitive, and does not require extensive training to use; this vocabulary should also be easy to use by those without design training. Therefore, evaluation of the vocabulary was be performed with a different group of participants with varied backgrounds and experiences, to establish if gestures in the consensus set were easy to perform and appropriate for the activities they were matched with.

The evaluation had two parts, as specified in Section 5.3.5. Gestures from the consensus set and the discarded set were evaluated abstractly in Part 1 of the evaluation. Participants were asked to perform the gestures using their hands while observing a photograph of the object they would imagine they were interacting with (objects were the same as those shown in Figure 5-3, and they were used consistently to gesture elicitation i.e. if a gesture was elicited for a specific object then it was evaluated for that object too). Then, although the goal of the study was to identify in-air gestures for conceptual design independently of the currently available technology, four variants of gestures for four key manipulative gestures were evaluated using a VR application developed at University of Strathclyde, in Part 2 of the evaluation. This was done to determine if interactions in the VR environment resulted in different evaluation outcomes, which would help determine future research objectives. Participants in the evaluation were asked to select their preferred gesture among the tested gestures for each activity, and a variant of the consensus set developed in Chapter 6 was created as an outcome.

Study robustness was also tested. As a number of different objects were used in the study it was explored if there was an effect of the shape of the manipulated object on the gesture performed.

Current CAD systems typically have a predefined sequence of activities and commands that need to be followed in order to create an object of a desired shape. As a part of the post study analysis, it was also explored if the object creation workflow of the gestures participants proposed for the free shape creation was different from that of the established CAD solid modelling practices. Findings from the analysis of the study robustness may help guide future studies in the field.

Parts of this chapter have been published in a journal paper[7].

7.1. Vocabulary (consensus set evaluation)

Ten non-designers were asked to evaluate the consensus set in order to reduce bias designers may have introduced. They had varied backgrounds (two researchers specialising in organisational management, two mechanical engineers, two electrical engineers, two architects, one marketing manager, and one teaching associate specialising in cost forecasting) and their average age was 33 years old. They had 1-15 years of professional experience in their profession (4.4 on average), and aside from one of the electrical engineers, no substantial experience using AR or VR environments. One architect and a marketing manager tried a VR system briefly in an event, which did not count as a substantial experience. Five participants have used CAD in the past (ranging from 2-10 years), but it was not a core element of their

[7] Vuletic, T, Duffy, A, Hay, L, McTeague, C, Campbell, G & Grealy, M, 'A novel user-based gesture vocabulary for conceptual design', *International Journal of Human Computer Studies.*

daily work in their current role. Architects used CAD primarily for layout of rooms in a building rather than 3D shape creation, manipulation or modification.

While all types of conceptual design include a process of creating forms, functions and behaviours to a certain extent (Benami and Jin, 2002), in different fields focus is not equally put on all of them. This study focused primarily on the form and visualisation of design concepts, and product design students that participated in the gesture elicitation have had extensive training in form generation, that did not necessarily have to have a link to function or behaviour in all stages of development.

In product design conceptual design is often referred to as a collection of activities that "determine the form of an engineering product" (French et al., 1985) or the initial stage of the design process, during which fundamental, but approximate, outlines and form of a product are created (Keinonen and Takala (2010), pg 17; Ulrich and Eppinger (2011), pg 18). Mechanical engineers primarily focus on the function as a solution to the problem generated via conceptual design (Chakrabarti and Bligh, 1994), or at least explore function and behaviour during conceptual design before they move on to form (Welch and Dixon, 1994). Architects may consider both form and function. However when they focus on form, particularly since computer generated forms have become a standard in the architectural design, form takes precedence over design optimization or manufacturing (Grobman et al., 2009). However, depending on the approach taken function can be linked to form, or form can be a separate entity superimposed on the function (Reveron, 2009). The latter would be similar to the form exploration observed in this study. When architects focus on the function, they focus on spatial configuration which is either defined by function or helps define the function (Reveron, 2009), and in these cases it is more akin to the approach taken in mechanical engineering (although the functions observed can have a very different nature). Hence, both mechanical engineers and architects were considered to be far enough removed from product designers to be considered appropriate participants in the evaluation, as they would introduce diversity both in training and mind-set.

Evaluation process was detailed in Chapter 5, Section 5.3.5. In Part 1 of the evaluation participants were asked to emulate the gestures with their hands and rate them for appropriateness for the activity performed and ease of performance, for both parts of the consensus set. In Part 2 of the evaluation they tested a number of gestures implemented in a VR application and evaluated the appropriateness for the activity performed, ease of performance, if the result of the activity was achieved and technical difficulty of gesture performance in the system used (basis for ratings are described in Section 5.3.5). For any activity where more than one gesture was tested, participants were also asked to choose a preferred one. They were free to provide any additional comments at any time, and all comments were noted. A visualisation of the author testing the VR system also displaying a setup participants used during the evaluation is shown in Figure 7-1. The raw data collected from the evaluation process can be found in Appendix H, Section H.2.

Figure 7-1 : Author testing the VR system

7.1.1. Evaluation Part 1 – abstract evaluation

Averaged ratings across all ten participants are given in Figure 7-2. The top half of the figure illustrated gestures with the highest agreement from Part 1 of the study and bottom half of the figure for the Part 2 of the study. Where more than one gesture was evaluated for an activity, the preferred gesture across the ten participants was denoted with a blue box.

For both parts, participants found majority of the gestures easy to perform, and average ratings were on the agree side of the scale. The scale was described in Section 5.3.5, and was a seven point Likert scale ranging from Strongly Disagree to Strongly Agree was used, where Strongly Disagree corresponded to a value of 1 and Strongly Agree corresponded to a value of 7 for numerical analysis.

Looking at the appropriateness of the gestures for the activity, average ratings ranged from strongly disagree for TD05, to mildly agree for S01.2, D01.2, and Drw01. However, observing the most frequently chosen preferred gestures and their average ratings, higher agreement ratings consistently coincided with the instances where participants on average preferred one gesture for a specific activity. Examples of these were TU01.1, TD01.1, TR01.2, ECS01.1, RCW02.1, RCCW02.1, ZI01.1, ZO01.1, S01.2, D01.2, Ext 16.1. In instances where there were disagreements between the participants on the preferred gestures, and multiple gestures were chosen, the average appropriateness ratings were still, on average, on the agree side of the scale. The examples of this are preferred gestures for EU03.1 and EU02.1, TL01.1 and TL 01.2 and ED01.2 and ED 01.1, which were chosen with similar frequencies. All *sculpting* gestures were rated on the disagree side of the scale, and Scul02 and Scul05 were selected with similar frequencies.

As the evaluation was performed primarily to evaluate the existing consensus set, participants were required to choose one of the gestures that they were evaluating without introducing changes to them or suggesting different gestures they would have preferred instead. However, they were free to provide any further comments on any of the activities they performed. Comments like “if I had to I would choose EU03.1, but I would prefer to only use one hand to extrude the object, and would not hold it with the other hand” or “I would prefer a different gesture” appeared frequently for the activities where there was no clear preferred gesture and where average appropriateness ratings were lower. In the instances were a single gesture was tested for the activity (due to earlier analysis showing it is much more frequently suggested during the full study), the average appropriateness ratings were on the higher end of the agree side of the scale, like for Ben02, Drw01, Res 01. This confirmed that the gestures identified from the study analysis were appropriate and acceptable to the evaluators.

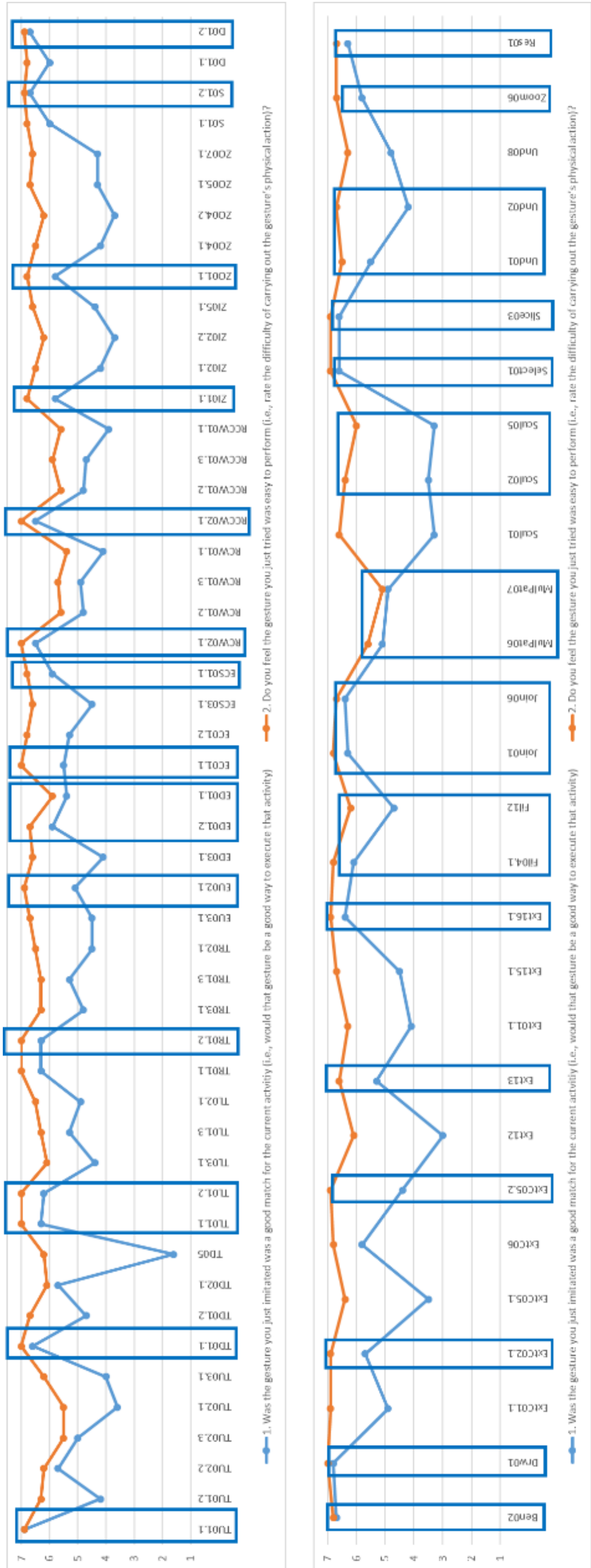


Figure 7-2 : Averaged ratings across the ten participants for the gestures with highest agreement from the Part 1 and Part 2 of the study

7.1.2. Evaluation Part 2 – VR based evaluation

List of evaluated gestures is provided in Section 5.3.5, and what participants saw in the system is shown in Figure 7-3.

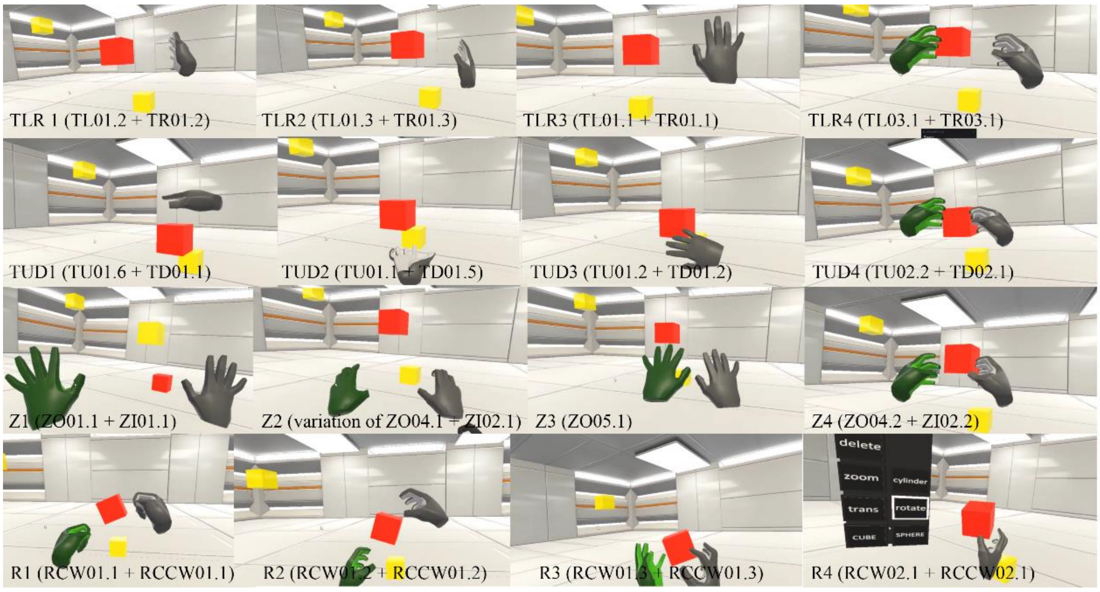


Figure 7-3 : Tested gestures visualised in the VR system

Averaged ratings across all ten participants for the evaluation of the gestures used in the VR application are given in Figure 7-4. Participants consistently rated gestures they had chosen as preferred as appropriate for the activity performed. Gesture evaluation via use of VR application had additional parameters, as participants were also asked to rate their satisfaction with the achieved result and the ease or difficulty of performance in the application.

Satisfaction with the achieved results and ease of gesture performance were on the positive end of the scale for the majority of gestures (above 5). All participants rated the outcomes as expected, they were satisfied with the achieved result. Out of 16 gestures, only one was rated as “neither agree nor disagree”, for the rest participants agreed the gesture was easy to perform. However, the ratings for ease or difficulty of performance of the gesture in the system, considering the VR technology, did not always follow the same trend. During the development of the VR application, it was noted that the combination of the Vive headset for visualisation and LEAP sensor for the detection of gestures (evaluation set-up was described in Section 5.3.5) were not able to detect grasping gestures as well as an open hand or a fist. Due to occlusion, detection of an open hand had proven more difficult when the side of the hand was the only surface detectable by the LEAP sensor. There were concerns this might have affected the satisfaction rates during the evaluation.

However, this did not seem to have had an effect on the choice of preferred gestures. For example, the discrepancy between rates for appropriateness of the gesture and difficulty of performance in VR was highest for RCW/RCCW 02.1 and Select01. For those activities the participants have rated the appropriateness, ease of performance of the gesture disregarding the technology and result achieved highly on the agree side of the scale (average value of 6.1/7 and 6.9/7 respectively), and difficulty of performance in the VR application low on the disagree side of the scale (average value of 3/7 and 3.7/7 respectively). They also commented that the gesture was hard to perform in the system, in terms of achieving the desired outcome as the system did not recognise the gestures accurately enough, but that they would prefer it if it worked well.

Nevertheless, there were also instances where ratings were lower than for all other gestures used to perform the same activity for all four parameters e.g. TL/TR03.1, TU02.2/TD02.1 or RCW/RCCW 01.3. For these, average values for appropriateness of the gesture for the activity 4.6/7, 4.8/7, 3.6/7; ease of performance 5.3/7, 5.1/7, 4.3/7; satisfaction with the result of the activity 5.2/7, 4.8/7, 4.5/7; ease of the use of the application 2.8/7, 3.1/7, 2.3/7, respectively). The comments participants made did not seem to indicate correlation between the difficulty of performance in the VR application and the decision to avoid the specific gesture as preferred for the activity. Instead, they tended to be linked to the desire use only one hand. However, in the future work it would be advisable to achieve comparable ease of use for all applied gestures before the evaluation takes place.

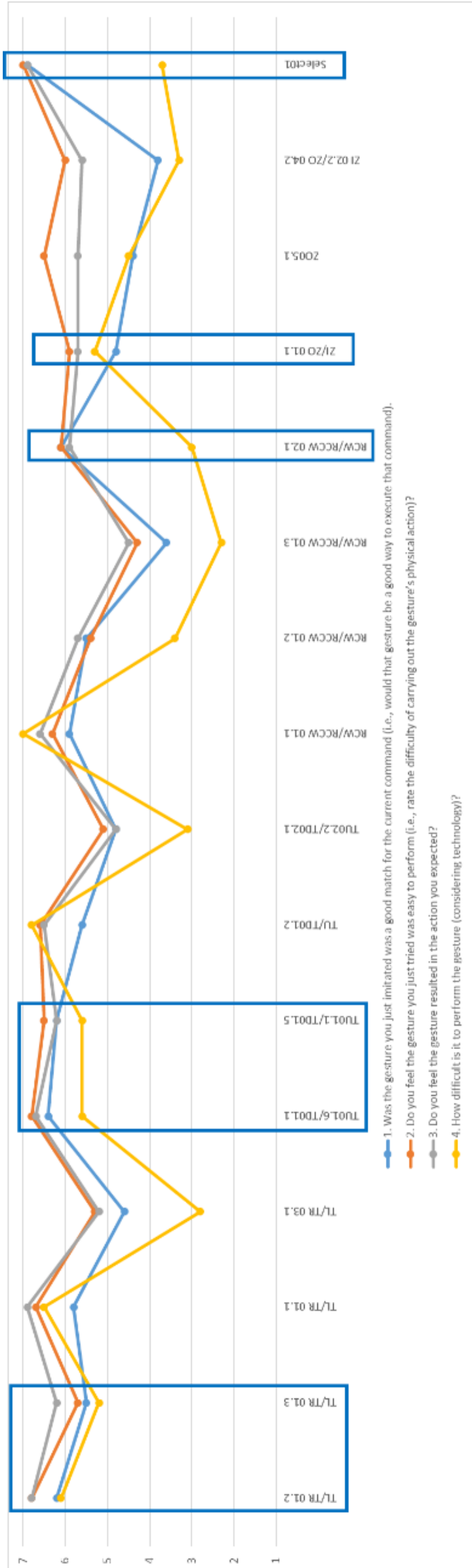


Figure 7-4 : Averaged ratings across the ten participants for the VR application

Six out of ten individual participants explicitly stated a preference towards using one or both hands, unprompted. Where this was the case, the majority of the participants (five out of ten) preferred to use one hand only as it was less tiring and more comfortable. One participant stated that using both hands was preferred as it gave them more control over the object. One participant stated that they would use both hands only if very precise motion was required, but would otherwise prefer one-handed gestures.

7.1.3. Variation of the consensus set including evaluation outcomes

The consensus set and the discarded set of gesture vocabulary given in Figure 6-12 and Figure 6-13, respectively were further revised. Gestures evaluated in Part 1 and Part 2 of the evaluation are marked with a green circle and a black circle to the left of the axis for each gesture, respectively, in Figure 7-5 and Figure 7-6. Gestures most frequently chosen as preferred were circled with a grey dashed line for the Part 1 of the evaluation, and a green dashed line for the Part 2 of the evaluation.

Only seven activities were evaluated in the Part 2 of the evaluation process; however, it was encouraging to see that for seven out of nine choices the evaluation performed in the VR system and in the emulated gestures were the same. Where they did not match, the gestures chosen in the VR based part of the evaluation appeared to take into consideration the similarity between the different gestures and the effect they would have on the object being manipulated more. For example, Participant 10 stated that the gestures TL/TR01.2 and TL/TR01.3 were very similar. They both include an element of the physicality of the object and appear to “push” it in a desired direction; the only difference is the orientation of the hand. However, if a physical object were to be pushed using either of the gestures, the effect would have been the same.

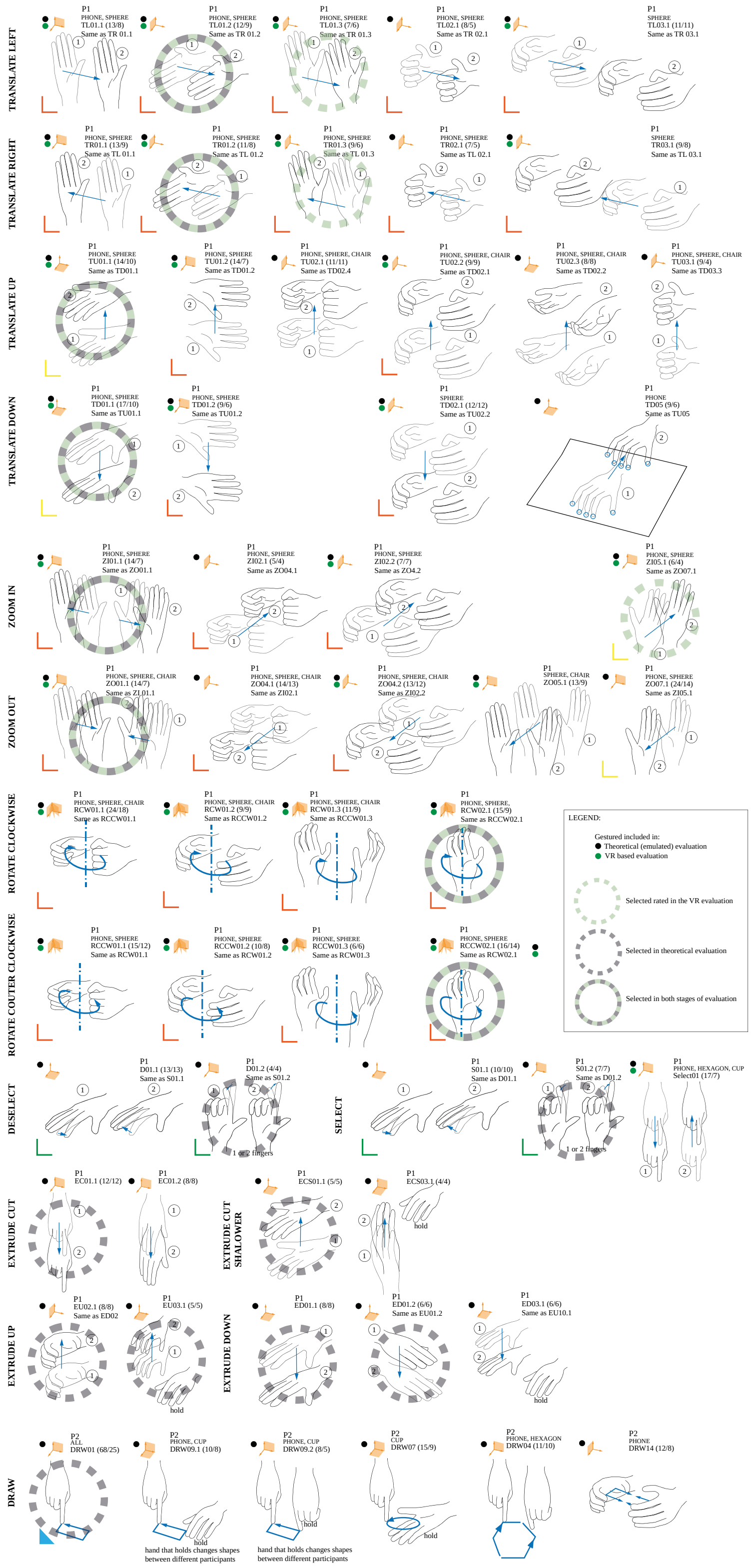


Figure 7-5 : Evaluated consensus set (see Figure 6-12 for original consensus set)

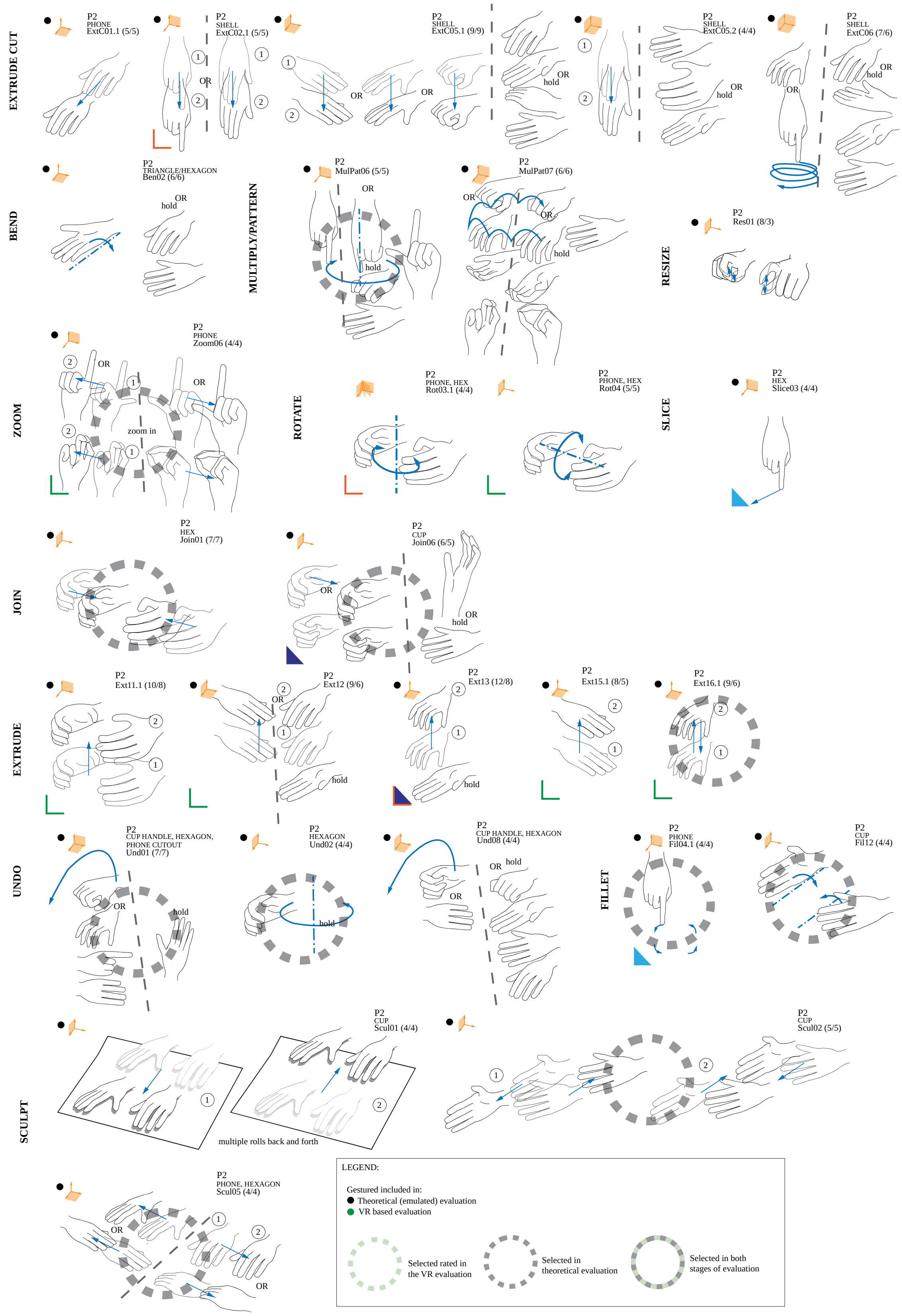


Figure 7-6 : Evaluated discarded set (see Figure 6-13 for original discarded set)

Taking both full study analysis and evaluation of gestures by non-designers into account, a variant of the evaluated consensus set was created, shown in Figure 7-7. Where selected gestures varied between VR based evaluation and abstract evaluation, both choices were retained.

Abstract evaluation relied on participant requirements exclusively and VR evaluation supplemented it with VR representation and introduced the element of practical application. Former evaluated the gestures in terms of imagined participant perceptions, the latter further tested those perceptions (for selected gestures) in an applied setting, and both should be considered in future research. The gestures from both consensus and discarded sets, compiled in Chapter 6 were tested, to ensure gestures were not eliminated prematurely, as the conditions during the two parts of the study varied. For example, Zoom06 and Ext 16.1 were not included in the consensus set; instead, they were in the discarded set, as the statistical analysis has not shown significant agreement that was high enough. However, they were included in the evaluation due to high repetition, and in the evaluation they were consistently rated as appropriate for the activity and Ext 16.1 was also chosen as a preferred gesture for the activity.

In Section 6.3 it was mentioned that sometimes one or two hands were used in gestures performed for the same activity, where the hand actually performing the nominal activity was performing the same gesture, while in the bimanual variants the additional hand was used to hold the object or a part of the object being modified or manipulated in place. It was argued that depending on the recognition methods used for gesture implementation in the future “holding” element of the gesture may become optional in the future in effect merging the gestures. Revisiting this discussion, EU03.1 in the evaluated consensus set (same as Ext 13 in the evaluated discarded set) and Ext16.1 in the evaluated discarded set were both chosen as preferred gestures during the evaluation, and represented variants of the same gesture with and without “hold”. Experiencing both in the VR environment, participants chose a unimanual gesture. In the abstract evaluation the exact equivalent of Ext16.1 did not exist, so it cannot be claimed that this finding has answered the question of if "hold" is required, however the argument that the application modality will have an effect on the variant of the gestures performed stands.

For the consensus set it was noticeable that most of the bi-manual gestures were eliminated, with the exception of gestures for *Zoom in* and *out* (ZI01.1 and ZO01.1), and one of the *Extrude up* gestures (EU03.1). Additionally, gestures that were more frequently performed for one shape only were not chosen as preferred by the evaluators. Additionally, majority of the chosen gestures included an element of dimensionality e.g. for the translation gestures, hands tended to use all three planes rather than just remain in the vertical plane the objects were initially showed in.

For dichotomous activities, where a specific gesture was chosen for one activity and not for its pair, both were retained e.g. ZI05.1 was chosen and its paired gesture for *Zoom out* ZO07.1 was not, but both were retained in the set. Where gesture was in the consensus set being tested, but originated in Part 2 of the study and was the only gesture of a specific category to be included in the set it was retained in the final consensus set if the rate for appropriateness of the gesture for the activity and the ease of performance were high (scored 6 or 7). The example of this is the gesture for *Selection* activity "Select01".

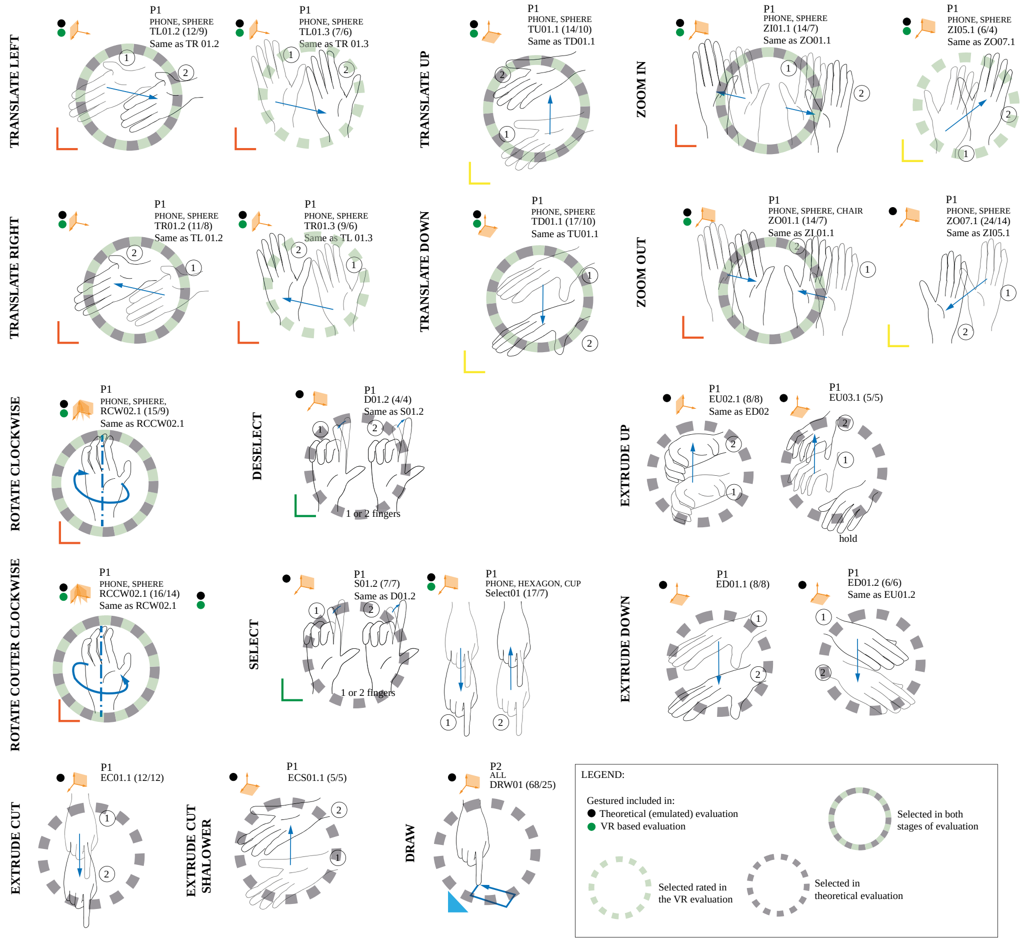


Figure 7-7 : Variation of the consensus set including evaluation outcomes

Discarded set evaluation results are given in Figure 7-8.

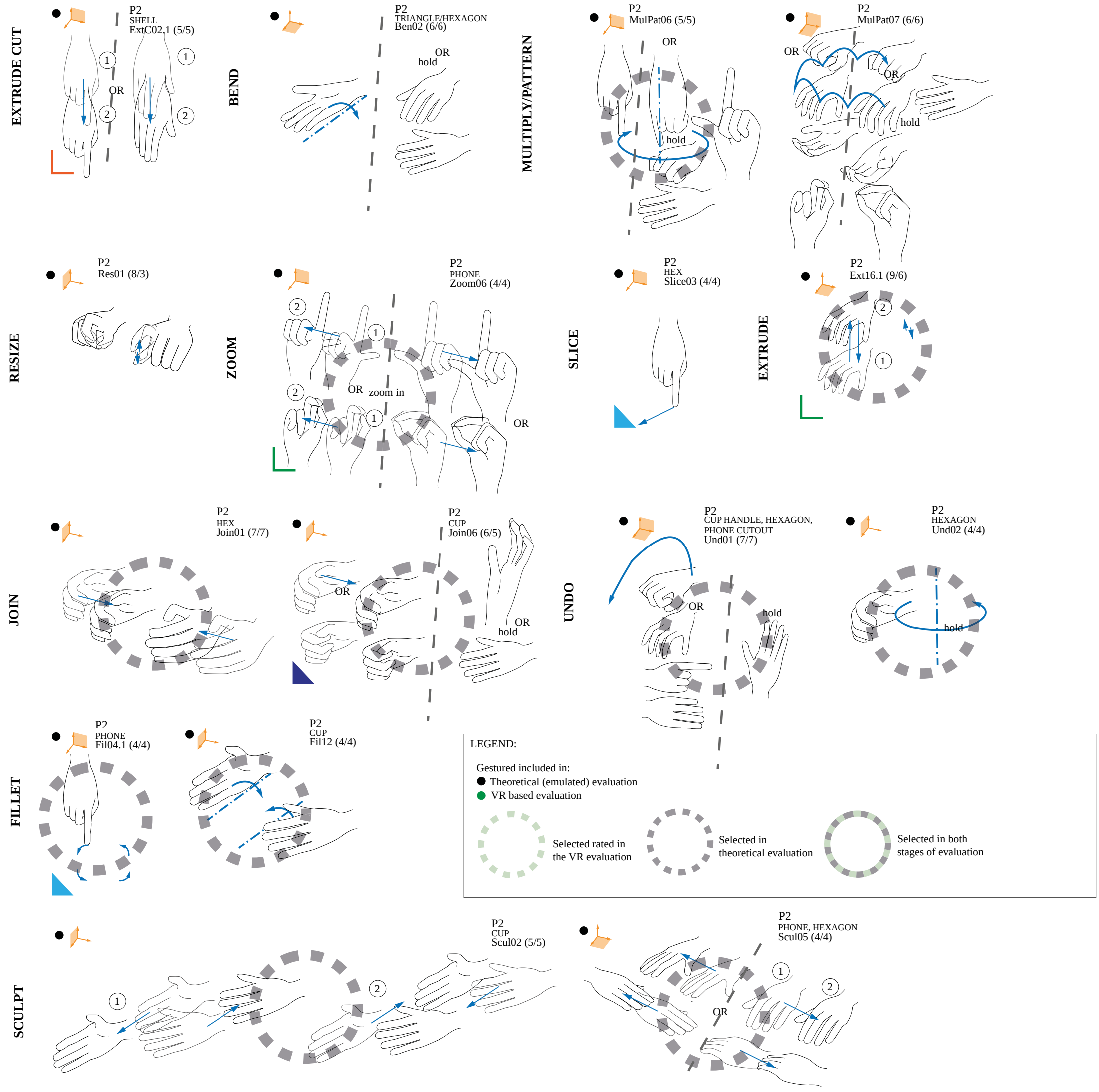


Figure 7-8 : Variation of the discarded set including evaluation outcomes

Bend, *Undo*, *Sculp*t, *Multiply/Pattern* and *Loft* were gestures that were initially not included in the refined consensus set due to low agreement during statistical analysis. Additionally, it seemed like majority of the gestures suggested for those activities have been influenced by the shape of the object being modified. This influence was described in Section 6.3. *Loft* had a very low number of repetitions (six different gestures were suggested by different participants, and one gesture was suggested by two different participants), making statistical analysis impossible, and was entirely excluded from the consensus set, as described in Section 6.3. The remaining three gestures were reconsidered for inclusion following the evaluation. Ben 02 and Und01 have had high ratings for appropriateness of gestures for the activity (6.7/7 and 5.5/7 respectively), MulPat06 and Mulpat07 were on the lower end of the appropriateness scale (5.1/7 and 4.9/7 respectively), while Scul02, Scul05 and Und02 were assessed as either not appropriate for the activity, or between appropriate and inappropriate (3.5/7, 3.3/7 and 4.8/7 respectively). Participants 1 and 7 have provided unprompted comments that for sculpt activity none of the gestures were ideal, and Participant 3 thought the same about multiply/pattern activity. Combined with the generally low estimates of appropriateness for these gestures, this, along with the statistical analysis not showing significant results has led to the decision to retain gestures for these activities in the discarded set. However, if further studies were to be performed to explore more detailed gestures relating further to the shape of the objects being interacted with, these would be a good addition to the set to analyse.

For *Extrude Cut* activity ExtC02.1 was chosen most frequently (four times), but the remaining three proposed gestures had just slightly lower results, and with ten participants taking part in the evaluation it was not possible to ascertain if it was genuinely the most appropriate gesture for the activity. For the *Extrude* activity, Ext16.1 was the clear choice for the evaluators, and compared to the *Extrude Up* and *Extrude Down* gestures from the consensus set, it was noticeable that it is a variation of EU03.1. Hence, it was added to the consensus set for both *Extrude Up* and *Down*. Two gestures for *Join* were chosen comparable number of times, four and six, as were two gestures for *Fillet*, five and five. Participant 10 commented that they were interchangeable, and Participant 3 believed they depended on the shape of the object that is being interacted with. As there was no clear choice, they all remained in the discarded set. Gestures for *Slice*, *Resize* and *Zoom* activities have been rated as appropriate for the activity, but as they were initially only suggested by three participants, they were included only to provide descriptive information about the gesture performed, and could not be added to the consensus set.

7.2. Study robustness

To test the robustness of the study, some of the activities were performed for more than one object. *Zoom in/out*, *Rotate clockwise/counter clockwise*, and *Translate up/down/left/right* were repeated for the irregular sphere and the phone, and *Zoom in*, *Translate up*, *Rotate clockwise* were repeated for the chair, phone, and sphere. This was done to observe if the shape of the object being manipulated or its recognisability had an effect on the gestures used for the interaction. The participants were asked about the effect shape and recognisability of the object had on their activities in the post study questionnaire, and their statements can be seen in the Appendix G, Section G.1. The list of performed gestures and comparisons between the gestures for the same activities and different objects can be seen in Appendix G, Section G.6.

To observe the effect of the shape of the object *Zoom in/out*, *Rotate clockwise/counter clockwise*, and *Translate up/down/left/right* activities were observed for the irregular sphere and the phone. 86% of the participants (38 out of 44) claimed that the shape of the object influenced the gestures they made. If the participant performed the same gesture for the same activity for both objects, it was assumed that the shape of the object did not affect the gesture use. If they were different, there might have been an effect. Out of 351 gestures for all of these activities combined, 123 have been performed in the same manner (35%). Around 68% of the participants that claimed there was an influence of the shape did actually perform different gestures to interact with different shapes, when average value between different shapes seen in Table 7-1 is taken. 50% of those that claimed that the shape did not influence the interaction with the object actually did not perform the same gesture for the same activity performed on the object of different shapes (if only *Zoom in* is observed this drops down to 0%). Four participants could not tell if the shape of the object had any influence on the gestures performed, and 56% of them performed the same gesture regardless of the shape.

Table 7-1 : Agreement between statement about interaction and actual interaction based on shape of the object (for the phone and the irregular sphere)

	Participants, out of 38, who claimed shape influenced interaction and interaction was different	Participants, out of 2, who claimed shape didn't influence interaction and interaction was the same	Participants, out of 4, who didn't know if there was an influence (and interaction was the same)
RCCW	32	1	2
RCW	30	0	1
TD	22	0	2
TL	24	2	3
TR	21	0	2
TU	29	0	3
ZI	24	2	3
ZO	24	2	2

Observing all three objects, out of 132 gestures for *Zoom in*, *Translate up*, and *Rotate cw* combined, 26 gestures were performed in the same manner (even lower – 20%). Of the 38 participants that stated the object shape would influence the gesture performed, 74% did perform different gestures for at least one of the different objects, as shown in Table 7-2. Only one of the two participants that stated they would perform the same gesture regardless of the object shape did so, and only to zoom out. Among the four that could not tell what they did, 33% performed the same gesture regardless of the shape. This would indicate that shape does have an effect on the performed gestures.

Table 7-2 : Agreement between statement about interaction and actual interaction based on shape of the object (for all three objects)

	Participants, out of 38, who claimed shape influenced interaction and interaction was different	Participants, out of 2, who claimed shape didn't influence interaction and interaction was the same	Participants, out of 4, who didn't know if there was an influence (interaction was the same)
RCW	34	0	1
TU	33	0	2
ZO	31	1	1

The sphere was the only object that was not used in everyday life or had an assigned function. Therefore, it was assumed that if recognisability was not playing a part in the gesture interaction with the object, a larger proportion of gestures used to interact with the sphere would have been performed in the same manner as the gestures used to interact with the phone and the chair. 21 out of 132 interactions were the same regardless of the object (16%). This may mean that recognisability of the object may have had an influence on the interaction type. Out of 22 participants who said they would interact with a recognisable and a non-recognisable object in the same manner, only 17% actually did perform the same gesture for interaction with the irregular sphere as they did for the phone and the chair. Fifteen participants who claimed they would have performed a different gesture for objects if they were not recognisable did do so, and 89% of them have performed different gestures for the sphere and the remaining two objects. Seven participants did not know what they did, and 20% have actually performed the same gesture regardless of recognisability of the object. This data is listed in Table 7-3.

Table 7-3 : Agreement between statement about interaction and actual interaction based on the recognisability of the object (for all three objects)

	Participants, out of 22, who claimed would interact with recognisable and non-recognisable object in the same manner (and interaction was the same)	Participants, out of 15, who claimed would interact with recognisable and non-recognisable object in a different manner (and interaction was different)	Participants, out of 7, who didn't know if there was an influence (interaction was the same)
RCW	3	15	2
TU	5	13	1
ZO	3	12	2

Overall, it seemed that different gestures have been performed if the object was not recognisable. However, the difference in shapes of the object might have influenced the interaction regardless of the recognisability and this may have been influencing the participants' activities. Recognisable objects used in this study, the phone and the chair had very different shapes and perhaps the shape did play a more important role for the choice of gesture than the recognisability of the object did.

The majority of participants that perceived their activities as different for different objects did perform different activities. Of those that did not, only around 50% or less actually performed the same activities. Of the participants who believed they interacted in the same way with a recognisable and non-recognisable object, only 17% actually did perform the same gesture. The majority that believed they performed different activities for different recognisable objects did actually do so, 89% of them. While these findings did not provide definitive information on participants' perception of their own activities, they did indicate that perhaps more focus should be put on objective measures rather than participants' perceptions of their own activity. Figure 7-9 illustrates that different gestures performed for the same activity by the same participant for a different object range between 35 and 38, indicating that the shape or recognisability of the object have likely had some effect on it (left hand side of the graph). However reported influence of the shape (middle of the graph) and reported influence of recognisability (right hand side of the graph), were at lower levels, illustrating the discrepancy between the activity performance and the participants' perception of their activities.

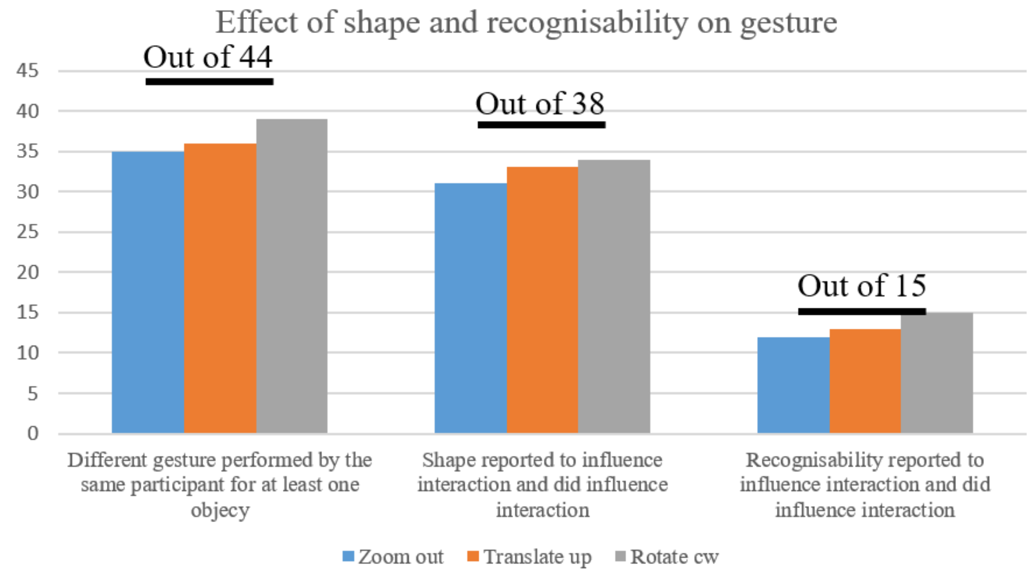


Figure 7-9 Comparison of statements about the performed gestures and performed gestures for all three shapes

7.3. Object creation workflow

In Part 2 of the study participants were asked to create one of the three objects shown to them: a cup with a handle, a hexagonal plate, or a mobile phone case. The cup and the hexagonal plate had two variants that were introduced in order to explore which gestures the participants would use to create solid shapes such as sphere and cube in the context of a more complex product. However, these were added at the end of the design process, and did not disrupt the workflow otherwise.

The Part 2 had two stages, as specified in Section 5.3.1 and illustrated in Figure 5-4. In the first stage, activities were partially guided (as shown in Figure 5-6 in Section 5.3.1) and in the second they were completely free, as only the final product was shown (as shown in Figure 5-7 in Section 5.3.1). This was done to enable the observation of the participants' workflow, and preferred choice and sequence of activities. The first stage directed the participants towards the established CAD workflow, focusing on the solid modelling design process. It was expected that in the second stage they would follow the same workflow if it was genuinely the most intuitive, and if that was not the case, other activities or sequences of activities may appear.

In order to reduce the likelihood of participants adopting the workflow from the stage one in the stage two, half of the participants performed the stage two first (the list of participants and the order of stage performance can be seen in the Appendix G, Section G.1). As each participant created two different objects, due to the combinations of objects and the number of participants, the number of times a specific object was created overall varied slightly, but it was comparable across the two stages, as shown in Table 7-4.

Table 7-4 : Number of different objects created in each stage

Object created	**Number of participants performing it in stage 1**	**Number of participants performing it in stage 2**
Cup with a handle	17 (7 of which had spherical handle)	16 (6 of which had spherical handle)
Phone casing	9	11
Hexagonal plate	16 (5 of which had the cubical stand)	16 (5 of which had the cubical stand)

Cup creation workflow is illustrated in Figure 7-11. Tables classifying steps and frequency of their performance were shown for guided stages in the top half of the figure and for free stages in the bottom half of the figure. Number of instances a specific workflow had appeared in is indicated above each workflow, and a short descriptor of each sequence is given in the orange box at the top of each collection of steps. Variants of the workflow sequence were classified using the first letter of the object, V for variant, and the number of the variant e.g. C for a cup, V for a variant and numbers 1-5 form variant codes CV1-CV5 shown at the top of the figure illustrating the cup creation sequences. Blue filled in boxes indicated a step was performed by a participant. Step titles that have been repeated by each participant that performed a specific workflow are bolded. Those that were repeated by at least half are bolded and have *. Steps that appeared in less than half of the instances of a specific workflow have an * in front of the step title and are not bolded. Steps that were performed at different time in the process for different participants, but the same activity was performed by all are shown in grey font e.g. fillet the edges in the

“Draw circle-extrude-shell-fillet-handle” sequence of the free stage for the cup. This convention was also followed in Figure 7-13 and Figure 7-15.

As visible in Figure 7-11, the cup creation workflow had two variants in both stages, and both appeared in the guided and in the free stage. In both, in the majority of cases, a cup was created by first either extruding (in 26 instances) a circular profile into a cylinder or sculpting a cylinder (in five instances), then ”shelling” that cylinder (i.e. retaining the walls and bottom of the cylinder but removing the top surface and the volume on the inside) and adding the handle. The form of the handle was different for the two variants, and that was noted in the classification tables. Sequences including extrusion and a traditional handle were classified as CV1and those with extrusion and spherical handle as CV3, in Figure 7-11. Sequences including sculpting and a traditional handle were classified as CV2 and those with sculpting and spherical handle as CV4, in Figure 7-11. In the free stage, one additional workflow emerged, classified as CV5 in Figure 7-11. In it, a larger and a smaller circle were drawn in the same plane, and then extruded to different heights to form the body of a cup. Then the handle was added. Two participants performed this sequence of activities.

The sequences of activities are graphically illustrated in Figure 7-10. The same convention for variant naming was retained as in Figure 7-11. Where only the last few steps were different between the sequence variants that was indicated by variant indicator above them.

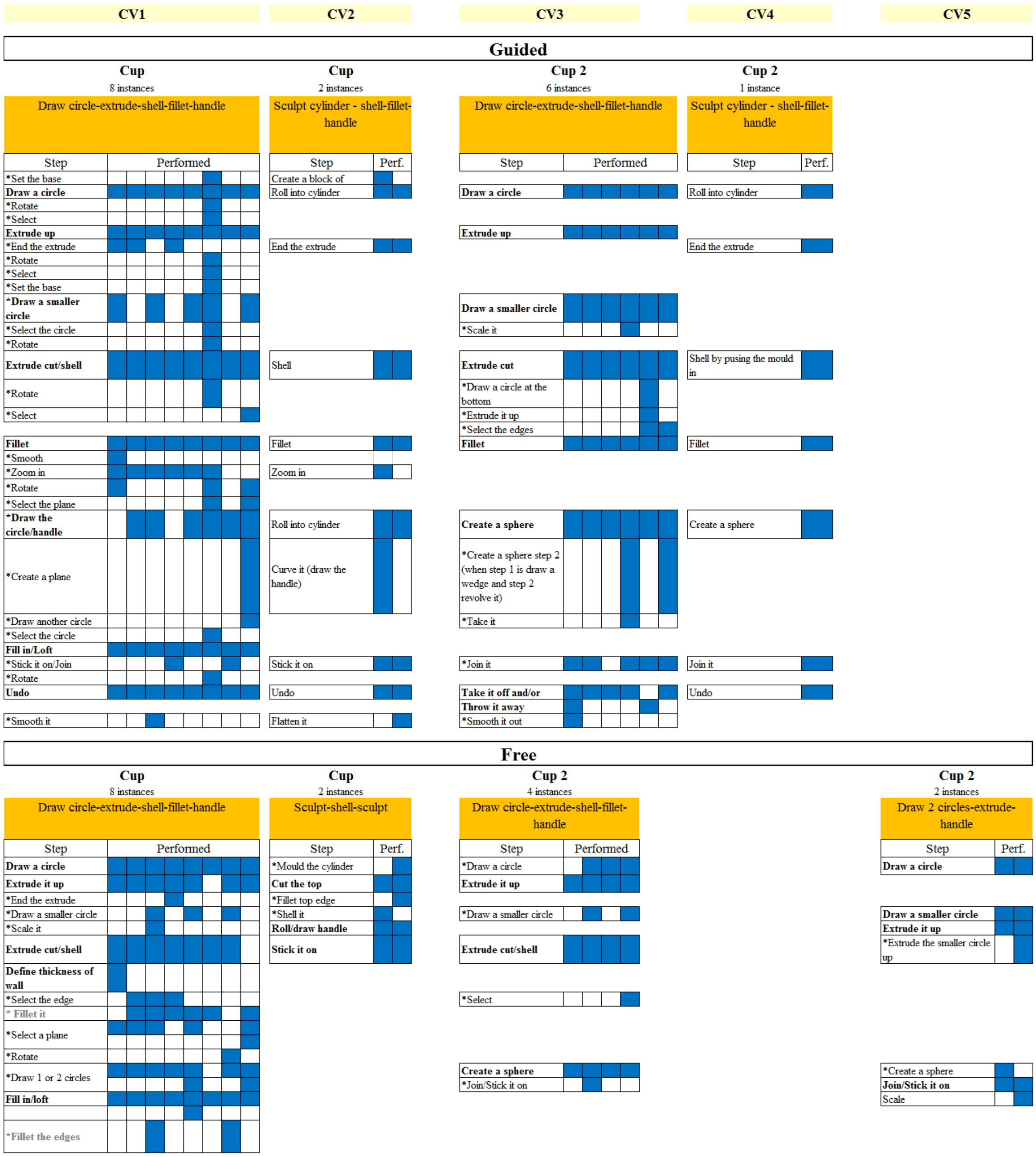


Figure 7-10 : Cup guided and free sequences

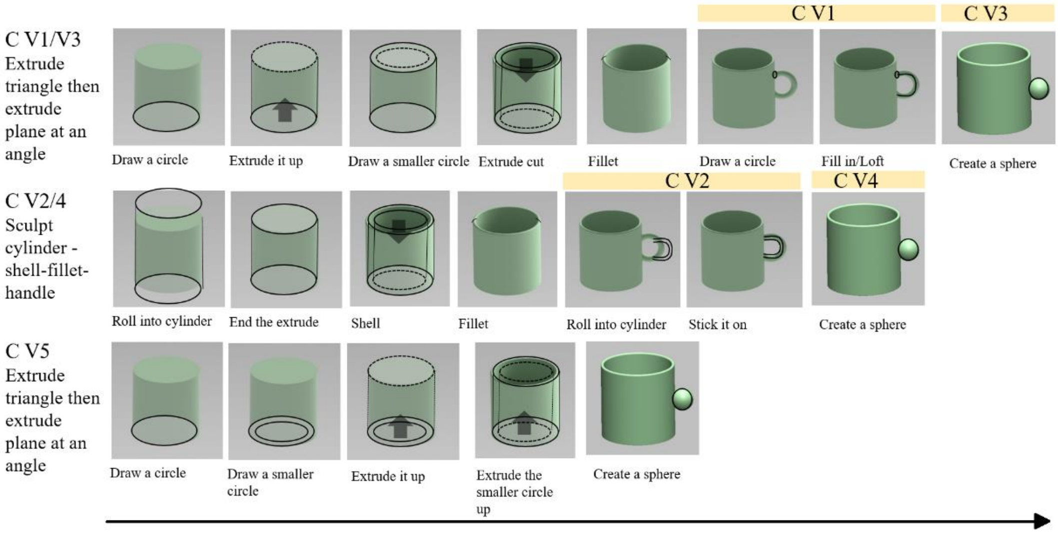


Figure 7-11 : Sequences for cup creation

For the phone casing (shown in Figure 7-13) and the hexagonal plate (shown in Figure 7-15) differences started to emerge. While in the guided stage all instances of phone creation followed the same workflow (classified as PV1 in Figure 7-13), additional four different variants appeared (classified as PV2, PV3, PV4 and PV5 in Figure 7-13). Two of the variants appeared in both guided and free stages (PV2 and PV3), and one was unique for each of the stages (PV4 for guided stage, and PV5 for the free stage). One to two participants performed each of the alternative workflows (five in total), while 14 participants overall performed the sequence classified as PV1. Sequences of activities are graphically illustrated in Figure 7-13.

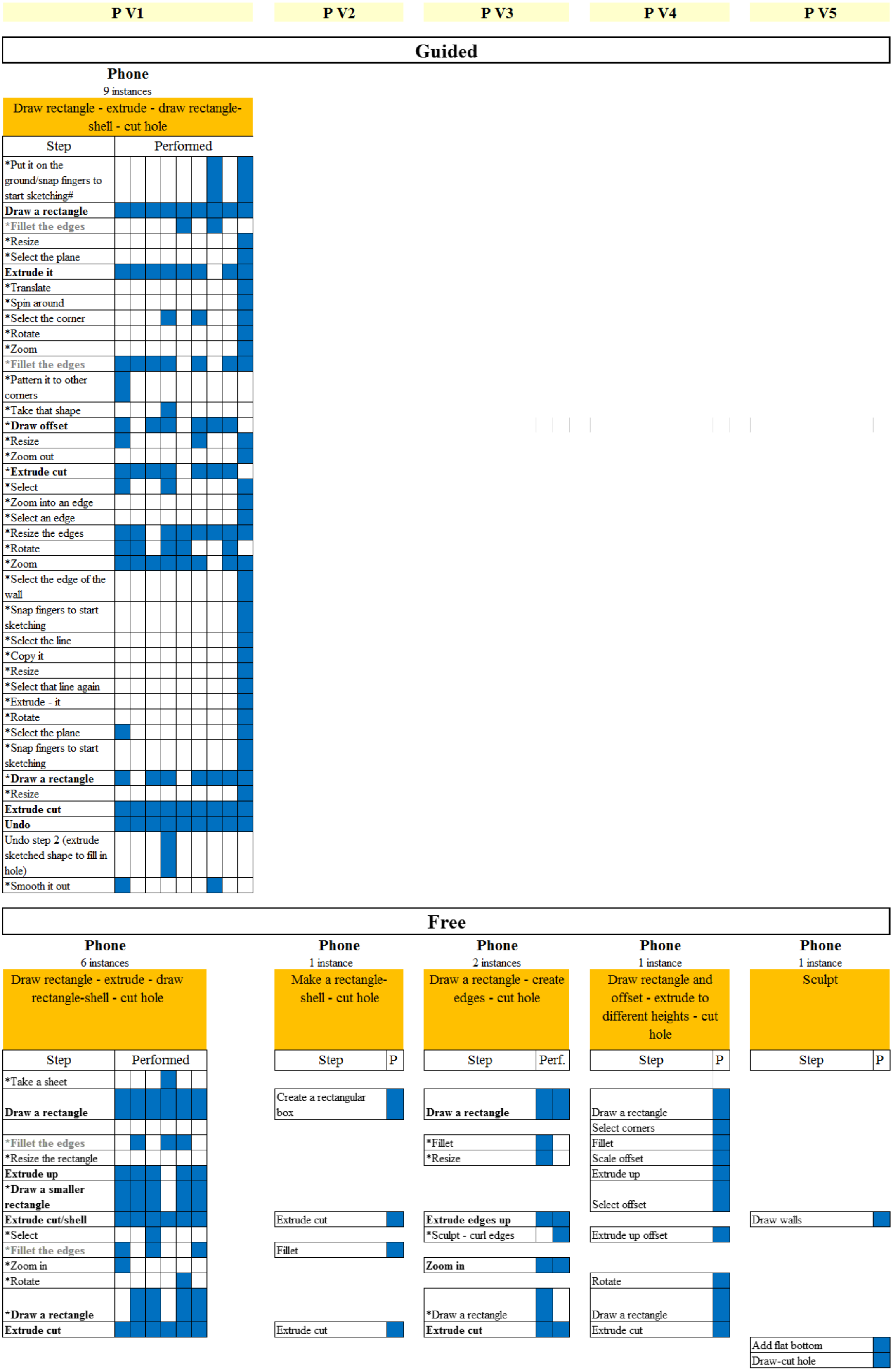


Figure 7-12 : Phone cover guided and free sequences

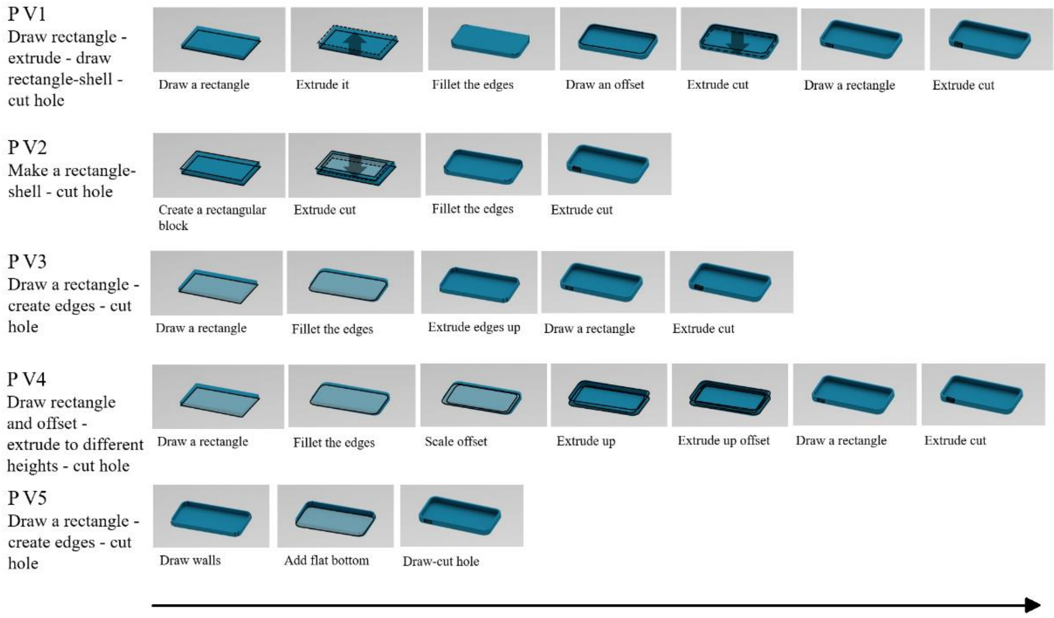


Figure 7-13 : Sequences for phone cover creation

For the creation of the hexagonal plate, the difference between the guided and free stage activities was the largest. In the guided stage, three variants appeared (HV1, HV3 and HV7, shown in Figure 7-14). In the free stage an additional six variants emerged (HV2, HV4, HV5, HV6, HV8 and HV9 shown in Figure 7-14). There were two variants of the hexagonal plate, in order to uncover the gestures proposed for a creation of a cube in the context of a product. However, in terms of activity, sequencing only the creation of the hexagonal plate without the stand is observed in both instances. Sequences of activities are graphically illustrated in Figure 7-15.

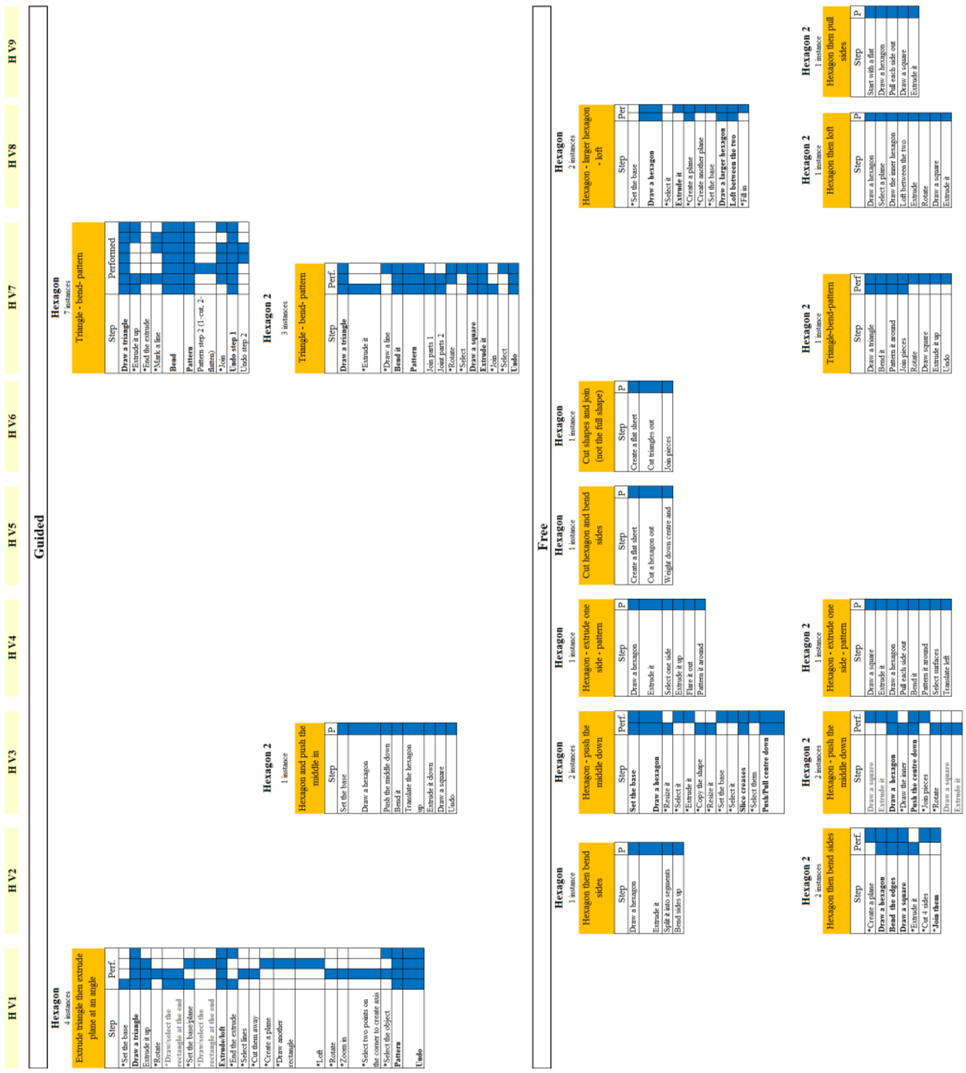


Figure 7-14 : Hexagonal plate guided and free sequences

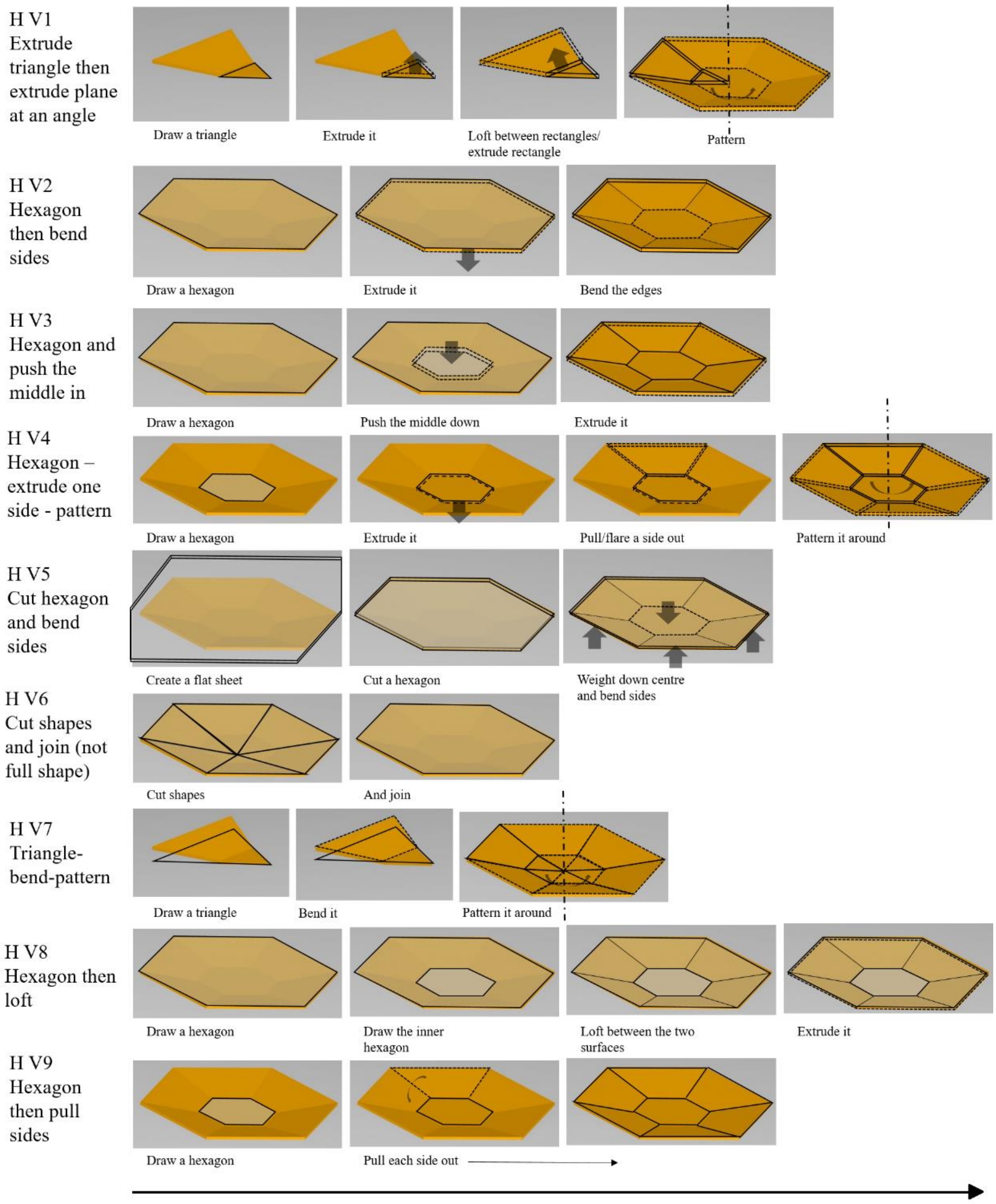


Figure 7-15 : Sequences for hexagonal plate creation

The majority of the sequences for the creation of the cut and the phone cover followed the steps that would have been followed if a part were created as a solid part using CAD (CV1/13, CV5, PV1-4, HV1, HV4, and HV8). In one sequence for the cup creation (CV2/2.4), to create the cylinder and the smaller cylinder that later became the cup handle, the parts were sculpted (“roll into cylinder”). When the hexagonal plate sequences were analysed, it was noticeable that a larger proportion of them included sculpting activities (HV2 “Bend the edges”, HV3 “Push the middle down”, HV5 “Cut a hexagon” and “Weight down the centre and bed the edges”, HV7 “Bend the triangle”, HV9 “Pull each side out”). In other words, they included manipulation of imaginary surfaces that resembled activities that would have been performed in physical reality, rather than creation of shapes using planes, surfaces and lines.

Participants were instructed to assume dimensioning would have happened automatically (“the room would know what size they want something to be”), hence the details such as sizes and distances, or omission of assigning thickness to surfaces were not taken into account while analysing the sequences. That bending a triangle was often performed assuming that both sides would remain flat surfaces was likely influenced by this instruction. In conceptual design, the goal was to convey the idea rather than the details. Hence, the assumption those geometrical definitions would remain while “sculpting” the elements was assumed valid in this study. However, there were also sequences where entire steps were omitted, and what was described would not have resulted in a full product displayed in the image shown to the participant (HV6 and PV5). Both of these instances occurred in the free creation stage.

The more frequent occurrence of “sculpting” in the creation of the hexagonal plate was linked to the complexity of the activities that would have been needed to be performed in a CAD system to create such a shape. In the creation of the cup and phone case, the planes used were parallel or perpendicular, and the shapes used were predefined in most commercial CAD systems. In the creation of the hexagonal shape, in which edges were angled at 30 degrees, that use of tools with higher complexity would have been needed along with the creation of additional planes positioned through specific points in space. Participants were expected to have less experience with the use of the more complex tools, and to have more difficulty visualising shapes where planes were coinciding at different angles than 90 degree or 180 degree angles. The findings seemed to support this, as out of the eight fully compliant outcomes for the hexagonal plate, five have used “sculpting”. This may indicate that current workflows for product design were not applicable to all the varieties of shapes that might be used in conceptual design. It also supported the idea that the kind of thinking required to follow procedural steps CAD systems require, and that required when visualising ideas that may change rapidly were different.

7.4. Summary

Evaluation of the consensus set was performed using abstract approach in Part 1, requiring users to emulate use of gestures while observing a photograph of the object they were meant to imagine interaction with. In Part 2, a VR application was used that allowed participants to test the gestures in the VR environment. Then they rated them for appropriateness for the activity they were preforming and ease of gesture performance.

Evaluation outcomes have shown that the participants find the majority of gestures easy to perform. When more than one gesture variant was tested for a specific activity, participants were also required to state what their preferred gesture was. Chosen preferred gestures generally were those that were rated highly for the appropriateness (above five on the scale of one to seven). For some gestures, for example *translate up/down/left/right*, preferred gestures differed between abstract and VR evaluation stage. VR evaluation choices tended to be the gestures that corresponded more closely with the three dimensionality of the objects being manipulated. If the preferred gestures from abstract and VR evaluation stages were different, when the variation of the consensus set including the evaluation outcomes was compiled both variants were included.

In the second part of the evaluation, two additional parameters were evaluated - satisfaction with the achieved result and the ease or difficulty of performance in the VR system. Satisfaction with the achieved result was consistently high (above five on a scale of 1-7 for 15 out of 16 gestures, and above four on the same scale for the remaining one) and similar to appropriateness and ease of gesture performance ratings for the specific gesture. Ease of performance in the application varied, as some gesture interactions within the applications had hand recognition issues that affected the performance. However, in these cases majority of the participants were able to disassociate the gesture from the implementation issues. They have stated their preference for the gesture they found the most appropriate, with a comment that it did not function well in the system, but they would have preferred to use it, if it had.

The outcome of the evaluation was a variation of the consensus set including evaluation outcomes, which took into account the non-designers perspective. It confirmed that the gestures in the original consensus set were easy to perform and considered appropriate, and provided indication of what types of gestures the language for conceptual design might benefit from focusing on if it were to target wider audience than just professional designers. Preference for single-handed gestures was observed during evaluation, with majority of participants perceiving two-handed gestures as tiring and unnecessary. This variation of the consensus set included a number of gestures that were initially discarded from the consensus set due to low measures of statistical significance, as they were rated highly during the evaluation. Revised and evaluated consensus sets, approach to the study design and the implications of the findings will be further discussed in Chapter 8.

Robustness of the study was evaluated based on the post study analysis of the effect of the shape on the gestures performed and the comparison of the object creation workflow when using gestures or when using a traditional CAD system. It was noticed that the shape, and potentially recognisability of the object being manipulated or modified might have influenced the gestures performed. This was inferred from the manipulative gestures each participant performed multiple times for three objects of different shape and recognisability. The effect of the object shape was noticeable for more complex modification activities such as pattern or undo, where the gesture performed was often not generic but closely linked to the shape of the object being modified. In the second part of the study, participants performed a partially guided creation of a shape and a free creation of a shape. It was found that in the free creation stage participants often diverged from the procedural sequence that would have been followed if the shape were to be created in a CAD system. This was particularly prominent when the shape created was more complex, i.e. contained surfaces that were not perpendicular to each other or shapes that were not standard. It can be concluded that if a new CAD system were to be developed that was to use in-air gestural interfaces, it would benefit from further exploration of the best design process to follow. Such a system may benefit from the introduction of sculpting or forming paradigms.

8. Discussion

This chapter explores the strengths and weaknesses of the research outcomes detailed in Chapters 6 and 7. It discusses the techniques and methodology applied, and further compares the approach taken and the work performed with the standard practices and established methodologies present in the field of HCI for in-air user gesture elicitation. This comparative analysis was used to validate the techniques and methodologies employed in the research reported on in this thesis. Then the future work and how research outcomes reported in this thesis may contribute to it are discussed.

8.1. Research outcomes

An aim and three objectives were set in the Section 4.4, and were addressed in the study and the evaluation of the consensus set, via addressing a number of tasks. This section will discuss how these objectives have been met.

8.1.1. Study Objective 1 - Identify the key elements of gesture vocabulary for form creation

This objective aimed to explore what would the gesture vocabulary for form creation look like and if it could be defined via user based gesture elicitation. It consisted of three tasks:

- Task 1.1. Identify gestures participants perform in response to the referent for creation, manipulation and modification of a number of 3D objects.

- Task 1.2 Analyse the identified gestures to achieve statistically meaningful, reliable, justifiable and repeatable results.
- Task 1.3 Establish a user defined set of gestures, a vocabulary, which aims to serve as a starting point for future conceptual design interface development.

Task 1.1. was addressed by the identification of gestures participants performed in response to the referents being shown to them. The full list of gesture descriptions and their sketches were given in the Appendix G, Section G.6. Then the gestures were classified and categorised using predefined taxonomy, thus addressing the Task 1.2, and the outcomes of this can be seen in Section 6.1, 6.2 and introductory part of Section 6.3. Statistical analysis was then applied to the categorised gestures and the outcome of this analysis can be seen in Section 6.3. Task 1.3 was addressed by a creation of a preliminary version of the vocabulary of design gestures, created based on the results of the statistical analysis, given in Chapter 6, Figure 6-12. Following the evaluation of the vocabulary by non-designer participants, evaluated variant of the vocabulary for non-designers was created, shown in Chapter 7, Figure 7-5. All three tasks were addressed successfully, completing the Objective 1. Strengths, weaknesses and lessons learnt during the research tasks are listed below.

Strengths of the research:

- 44 participants performed the required activities. This is a substantially higher number than typically found in elicitation studies (usually ~20 participants). Significant agreement was reached for majority of activities (68%). Further statistical analysis indicated the agreement did not happen by chance and there were commonalities between preferred gestures for the same activities between different designers.
- Coding scheme relied on taxonomy established in the field, updated for in-air gestures for conceptual design, enabling comparisons with existing research in the field.
- Three coders completed 10% of the sample in order to establish the coding baseline, confirm the sufficient inter-coder reliability was reached and increase the coding process uniformity, potentially increasing its objectivity.
- Statistical analysis used to establish a gesture vocabulary consensus set has been established in the field.
- Initial gesture vocabulary consensus set has been evaluated by non-designers, confirming that the gestures were easy to perform and fit for purpose.

Potential weaknesses of the research:

- Majority of the participants (38 out of 44) were from the same institution which may have contributed to the levels of agreement.
- Experiment setup did not allow participants to focus on details e.g. set dimensions or position features accurately. While this is generally not the key characteristic of the conceptual design, a number of participants noted that they may have acted differently if they were required to be more precise or dimension objects. This should be considered for future activities.
- In order to complete a comprehensive analysis inclusion of wider variety of distinct shapes would be required. This would particularly be the case for interactions shown to relate to the shape of the object being manipulated e.g. *Pattern*, *Bend*, *Undo*. Objects currently included covered limited variety of shapes, but larger variety would be required to identify potential different variants for activities where gestures were influenced by the shape of the object.

Lessons learnt in the process:

- Majority of the participants (39 out of 44) stated that they did perceive objects as if they were 3D, although they were shown to them on a 2D screen. While this indicated that the results were valid, it may be interesting to perform the same study in a more immersive environment and compare the findings.
- While the goal of this study was to find the most appropriate gestures regardless of implementation technology limitations, some technology limitations may eventually materialise. In the future, at a point where implementation becomes a consideration, the vocabulary may need to be reassessed for those limitations.

8.1.2. Study Objective 2 - Establish if the form of the objects interacted with affects the gestures performed to test study robustness

This objective aimed to explore if the shape and recognisability of objects interacted with affected the gestures performed via two tasks:

- Task 2.1 Observe if the form of an object affects the type of interaction.
- Task 2.2 Observe level of agreement between participants' perceptions of their own activities and the actual activities performed.

Gestures used for interaction with objects of different shapes or levels of recognisability were in majority of cases (over 65% at the minimum) different (Task 2.1). This was also confirmed by the participants' responses in the post study questionnaire where the smallest number of participants that stated they would interact with a different shape or a more/less recognisable object differently was 68%. However, generally the level of agreement between the activity performed and the participants' perception of the activity performed post study ranged between 17 and 89% (Task 2.2).

Strengths and weaknesses for these tasks are shared with the tasks 1.1 – 1.3, with one additional lesson learnt:

- It may be beneficial in future research if questionnaires were not used as a sole source of data, as the differences between the perceived (stated) and performed gestures for specific activities did materialise These could introduce errors to the analysis i.e. analysis of the stated and the analysis of the performed activities may lead to different conclusions. This may also mean that studies where participants explain how they would interact with an object without attempting to perform the gestures may not be entirely reliable.

8.1.3. Study Objective 3 - Explore the object creation workflow when participants are not confined by the procedural rules of a CAD system

This objective aimed to explore if established procedural rules used in CAD systems should be carried over into future systems to be developed the conceptual design via two tasks:

- Task 3.1 Compare the activity sequence between guided and free object creation.
- Task 3.2 Provide recommendations for the improvement of procedural rules for the conceptual design stage.

Task 3.1 was addressed via analysis and classification of sequence of steps participants have performed in the guided and free sequences of the Part 2 of the full study, in Chapter 6. Established sequences present in the CAD systems did materialise, but they were supplemented with sequences more akin to those performed during sculpting for some objects. Task 3.2 was met by further analysing these findings. It was found that as the complexity of the geometrical shapes of the objects had risen, the sequences diverged from the CAD procedural sequences and instead resembled sculpting of forming workflows. This indicates the need for further research in order to discover the most appropriate activities for formation of more complex objects that may enrich the gesture vocabulary for form creation.

Strengths and weaknesses for these tasks are shared with the tasks 1.1 – 1.3, and two additional weaknesses were identified:

- Majority of participants did not feel the need to manipulate the objects (rotate or translate them between modification/creation steps), and this meant that the data on manipulative gestures within a design sequence had not been collected to the same levels as during the Part 1 of the full study.
- Not all of the participants created the shape to the specification. Some participants did not perform some of the transitionary steps, particularly in the free stages. For example when creating a phone casing in the free stage (Figure 7-12 and Figure 7-13), 3 out of 11 participants did not define the shape being cut out of the side of the casing, reducing the pool of sequences to analyse for that particular activity.

8.2. Research methodology and techniques

Approach chosen to follow in this thesis aimed to identify most natural and intuitive gestures that were not influenced by what is currently possible in terms of technology. This section will compare the methods and techniques used to do this with the state-of-the art in the field of gesture elicitation for HCI. It will highlight the similarities and differences and discuss why the approach taken is valid.

8.2.1. Comparison with the taxonomies used in related research

Existing in-air gesture elicitation research typically followed the approach developed by Morris and Wobbrock (Morris et al., 2010, Wobbrock et al., 2005, Wobbrock et al., 2009), in which in-air gestures were classified using a number of established parameters, and then analysed using level of agreement metric, or the improved version of it called agreement rate (Koutsabasis and Vogiatzidakis, 2019). This approach has been followed in this thesis, with a number of modifications applied to it (detailed in Chapter 5).

The key difference between the work the approach was developed for and the work reported in this thesis is the dimensionality, as Wobbrock et al. (2009) worked on gesture elicitation for surface interaction that was largely two-dimensional. However, their approach has been widely adopted in the HCI field and a number of studies have been published using it to deal with three-dimensional motions. Some of these are Piumsomboon et al. (2013) exploring gestures for AR environments, Dong et al. (2015) for elicitation of mid-air gestures for TV control, Dim et al. (2016) for elicitation of mid-air gestures for TV control for blind people, and Jahani and Kavakli (2018) for descriptive mid-air interactions. This confirmed the approach was valid, in terms of established practices employed in the field. The changes introduced to the approach by different authors for different purposes were explored, and in some cases, it was decided to adopt them. In other cases, it was decided to revert to the established approach.

For example, Piumsomboon et al. (2013) introduced symmetry, which was adopted in this thesis. They focused on AR interaction that in some cases meant that the definition of binding, i.e. dependency of the gesture in relation to world around it, is needed. Study set up reported in this thesis excluded the need for this, as all gestures were object centred by design. That taxonomy category was retained, but was largely obsolete.

Jahani and Kavakli (2018) have adapted the form classification, and introduced descriptions that are more complex in order to classify the paths more accurately. Following the analysis of their approach, it appeared that the level of granularity they have chosen in definition of the gesture was too high, and what they would consider to be a single gesture was defined in this thesis (and in work by Wobbrock et al. (2009) and Piumsomboon et al. (2013)) as two or more gestures. For example, Jahani and Kavakli (2018) state that the gesture illustrated in Figure 8-1 describing the form is Co-Dynamic and Static Pose, where hand pose changes in one location then it is held there. This was because they included the act of forming the pose shown in the figure from a resting position as a part of the gesture.

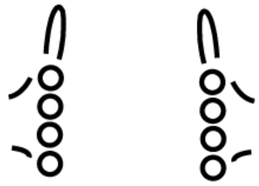


Figure 8-1 : Gesture used to hold an object, coded as Co-Dynamic and Static Pose

In the classification applied in this thesis the hand pose shown would be classified as a Static Pose. If the motion performed to form hand pose shown in the Figure 8-1 had a meaningful action assigned to it related to the object being manipulated or modified, then that gesture would have been classified as a separate gesture and a Dynamic Pose. Otherwise, it would have been considered as a preparatory gesture for pose formation and would not be classified at all. Existence of these gestures would be indicated by the connecting gestures precluding or following the gesture, and classified under that part of the taxonomy. Hence, the original classification for path definition by Wobbrock was adopted, although two classes were eliminated from it, as they were obsolete for the three-dimensional activity.

Dim et al. (2016) ultimately achieve their goal of defining gestures for TV control by blind people, and had their own taxonomy for the nature of gestures. However, their taxonomy for nature of gestures did not correspond to the established definitions followed in this study, and it was not adopted here, or discussed further here. Remaining studies followed the nature of gestures taxonomy developed by Wobbrock. Study reported in this thesis introduced a modified taxonomy of nature of gestures, more appropriate for gestures used for form creation. Here the primary identifier was if the gesture would need to be learnt prior to use because it is symbolic, semaphoric, metaphoric or abstract, or if it would not need to be learnt because it imitates a gesture from a physical world. Hence, all gestures that included a level of abstraction were grouped under iconic gestures, and were not further decomposed into symbolic, semaphoric, metaphoric or abstract at this stage. Physical gestures are called pantomimic here, as the hands pantomime the motions they would have, presumably, performed in the physical world. An intersecting type of pantomimic gestures that included a level of abstraction as they were emulating a different, but logically equivalent, activity than that performed was identified i.e. pantomimic gestures that conveyed a metaphoric meaning – metaphorical pantomimic gestures. A more extensive explanation of the taxonomy re-naming process was given in Section 5.3.4.1.2.

Only a few examples of changes to taxonomy are given above, as reasoning for changes for each taxonomy category was already given in Section 5.3.4.1. Instead, the differences between established practices and the approach used in this thesis, along with the justification for the change were summarised and shown in Figure 8-2. Grey text in Figure 8-2 indicates the elements of taxonomies that were not taken forward, and changes are denoted in bold font in a blue box in the left column.

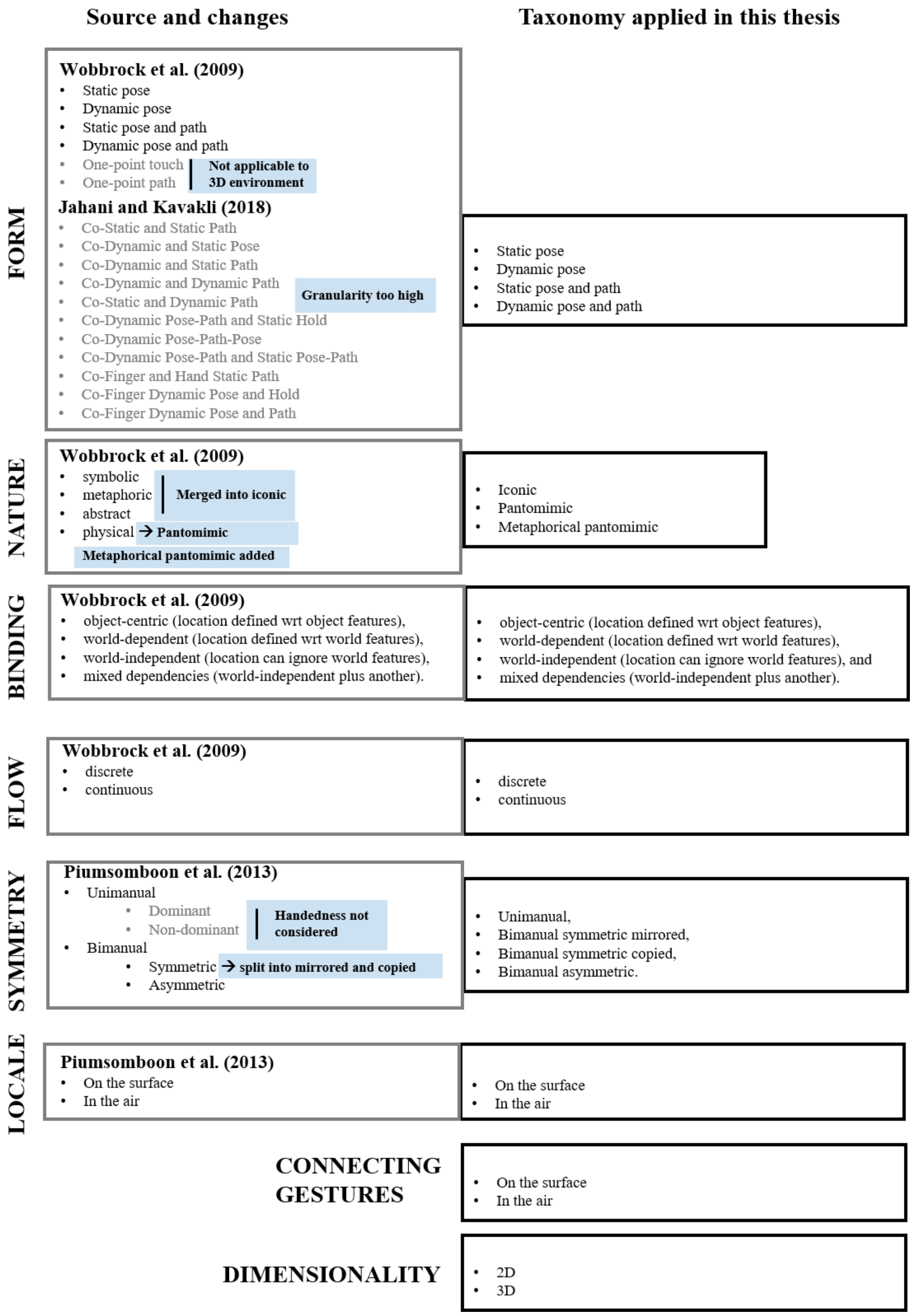


Figure 8-2 : Sources for taxonomy and changes to it

8.2.2. Comparison with the other gesture elicitation studies for conceptual design

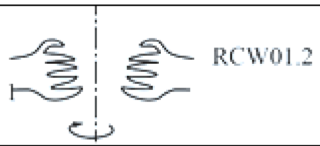
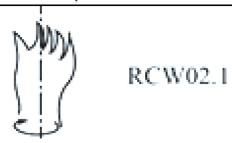
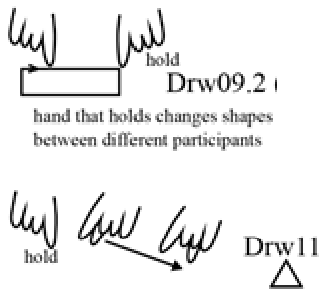
One paper, by Khan and Tunçer (2019), was identified that explored the gestures for 3D modelling in conceptual CAD. While the focus of this thesis is not CAD in particular, although it is imaginable that CAD may be a vehicle for implementation in the future, the work reported in the paper was analysed for similarities and differences in relation to the work reported in this thesis. While (Khan and Tunçer, 2019) have compared their findings to findings by Morris et al. (2010), indicating the same methodology was used, this is not evident in the paper. The authors refer to different gestures performed for the same activity as a theme, but it was unclear from the paper what the methodological approach for classifying different gestures under the same themes was. Additionally, in some instances, gesture types (in terms of nature of gestures) were mentioned e.g. mimetic, but the full taxonomy used was not given. Khan and Tunçer (2019) explore gestures along with speech, while the study in this thesis observes gestures on their own. As the methodology followed in the paper by Khan and Tunçer (2019) was only partially described, it was impossible to state how similar or different the methodology followed in this thesis was. It was likely that both studies took the approach set out by Wobbrock and Morris, however the gesture coding, classification and categorisation process followed in the studies may have been different (based on the available information).

Khan and Tunçer (2019) also begin their research with the assumption that conceptual modelling is performed using AutoCAD, Sketchup, 3DsMax and Solidworks. This is not in agreement with the findings from the literature review in this thesis which showed that conceptual design is usually not initially performed using CAD systems, but instead the designs move to CAD systems when they are already well defined.

Khan and Tunçer (2019) defined gestures using poses adapted from work by Braem et al. (2000), which were hand poses used when conducting an orchestra. It is unclear why these were considered appropriate for conceptual design, or if they fully describe poses that could appear in that context. Some examples of gestures are: C (hand forming the letter C), flat, index, flat-hold, pinch, fist, triangle, and L (hand forming the letter L). Work performed in this thesis takes a different approach, as gestures identified in this thesis were not matched to a predefined gesture vocabulary. Participants instead had a theoretically unlimited pool of gestures they could create and vocabulary was created as gestures were suggested by the participants. There are two possible implications of this on the gestures identified: (1) Mapping the gestures onto an existing vocabulary may lead to higher level of interpretation and grouping of similar but not same gestures under the same categories, (2) This propagates to the calculations of agreement rates, as they may be artificially inflated. Keeping the vocabulary open and not matching gestures onto an existing vocabulary increases the likelihood of identification of the natural and intuitive gestures.

Some gestures identified for the same activities matched i.e. two rotating gestures, one zoom in, one zoom out, a draw gesture, and an extrude up gesture, but activities observed in the two studies only overlap partially (5 activities are the same), and both studies contain additional activities not contained in the other study. Three additional gestures were added to the consensus set in the study by Khan and Tunçer (2019) that were not a part of the consensus set in this thesis, but were suggested by participants during elicitation. Table 8-1 shows the matches between the gestures selected by Khan and Tunçer (2019) and gestures proposed during the gesture elicitation performed in the research reported in this thesis.

Table 8-1 : Matching gestures identified between the studies by Khan and Tunçer (2019) and the one reported in this thesis

Gesture chosen for the activity by (Khan and Tunçer, 2019)	**Same gesture proposed during the gesture elicitation study reported in this thesis**	**Gesture sketches**
Zoom in	Included in the consensus set, 7 participants suggested it	
Zoom out	Included in the consensus set, 9 participants suggested it	
Rotate 1	Included in the consensus set, 9 participants suggested it	
Rotate 2	Included in the consensus set, 9 participants suggested it	
Freeform 1	Included in the consensus set (as draw), 25 participants suggested it	
Extrude prism/cone/box 2 (Second step of prism/cone/box 2)	Included in the consensus set, 3 participants suggested it	
Freeform 2	Not included in the consensus set (as draw), but 5 participants suggested it for a rectangle sketch, and one for a triangle sketch	
Extrude box 1 (second step of box1)	Not included in the consensus set, but 1 participant suggested it	
Extrude box 3 (second step of box 3)	Not included in the consensus set, but 1 participant suggested it	

Study by Khan and Tunçer (2019) results in 12 activities, with 2-3 gestures in the vocabulary for each. This thesis results in a vocabulary for 15 activities, with 2-6 gestures suggested for each activity. Overall, conclusions from these two vocabularies diverge. One of the key outcomes of Khan and Tunçer's (2019) work was that "most participants employed bimanual gestures not just for 3D referents but also for tracing closed shapes such as circle". Outcomes of the study reported in this thesis, showed that bimanual gestures were used in 52% of the gestures, and 48% were unimanual. Both types of gestures appeared for all activities included in the study. However, during the evaluation, a preference for one-handed gestures was discovered for the non-designers.

The opposing conclusions may be due to differences in methodologies followed, or due to the differences between the participants. Participants in the study by Khan and Tunçer (2019) had engineering and architecture background (although it is unclear what their experience level was). Gesture vocabulary was evaluated by four experts with the same background. In the study reported in this thesis, designers suggested the gestures and non-designers evaluated them. The study reported in this thesis also had a higher number of participants (44 participants) than the study by Khan and Tunçer (2019) (20 participants), and this may have influenced the findings. Finally, the study in this thesis focused on gestures only, and Khan and Tunçer (2019) also observe and allow speech. These were all possible causes for the divergence of findings, however, due to lack of information about the methodology followed in the study by Khan and Tunçer (2019), a more detailed analysis of the discrepancies between the findings cannot be completed.

Research by Hou et al. (2019) elicited hand gestures for virtual assembly, not conceptual design specifically. However, some of the activities for creation and manipulation of simple 3D objects were shared between their work and the work reported in this thesis. Activities shared include creation of a point, line, surface or geometry; selection, translation, rotation, cut, copy split and scaling of an object. The activities were chosen for inclusion based on the rankings elicited form two experienced mechanical engineers. Gestures for these activities were elicited from 14 students who had no prior experience with in-air gestures (their background or expertise was otherwise not discussed). The participants performed the gestures while using a HTC Vive system with a mounted LEAP sensor for gesture detection. The participants were instructed disregard operational accuracy or technical difficulties; however, it is unclear what the system actually displayed to participants of what kind of response they would receive when they perform the gestures. It was mentioned they were shown animations and that they narrated their activities, but there is not enough information reported to fully understand the experiment design.

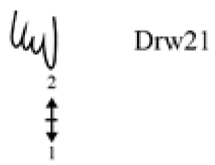
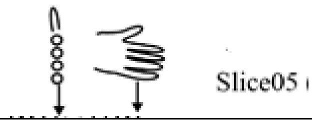
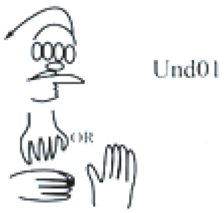
Due to lack of information, it is not possible to compare the studies fully. It is possible that both the study reported in this thesis and the study reported in the paper by Hou et al. (2019) were based on animations viewed by the participants, albeit the animations may have been in the VR environment in the study reported in the paper. The evaluation was performed using HTC Vive with a mounted LEAP sensor in both studies. Once the experiment was done the participants in the study by Hou et al. (2019) were asked to rate "learnability, match, easy-to-perform and fatigue of gestures", and rank them from best to worst. It is unclear what the criteria for the best to worst ranking were. Gesture categorisation process during the analysis was not described in the paper, other than the statement that any disagreements were resolved by a third expert, so the categorisation process approaches cannot be compared.

AgR values for the gestures were calculated. *Scale the object, freely rotate the object*, *single selection, freely move the object*, *create a circle* and *create a square* activities were similar to those explored in this thesis that had AgR ratings above 0.1 (ranging up to 0.225). *Delete* activity in the paper matched some of the outcomes of the *Undo* activity in this thesis. To select the gestures for inclusion in the consensus set, they were then rated for "order, popularity, preference, learnability, match, effort, subjective fatigue". A table showing these ratings and top scoring gestures was compiled, but most of the shared activities did not appear in it. The only ones present were create a square, create a circle and cut. It is unclear why this is, presumably although they scored high in AgR ratings, they did not score highly when rated for additional parameters. The gestures that were selected were then evaluated by a different group of 20 students (background not specified, hence no participant comparisons can be made), who viewed a "video description" of each command, and rated them for "learnability, match, ease and subjective fatigue". These gestures were then added to the user-defined gesture set (equivalent to the consensus set in this thesis). The weakness of this approach is that, other than the AgR, metrics used could have introduced a measure of subjectivity. In this thesis, statistical analysis was used in addition to the AgR and the consensus set was revisited following the evaluation to explore if some of the eliminated gestures were chosen as appropriate by the non-designers. However, the author does not believe a justification exists yet for reintroduction to the consensus set without a more extensive study exploring additional shapes.

Gestures for *creation of a circle*, *square*, *cube*, *cylinder*, *split*, *copy* and *cut* are the gestures that are shared between the research by Hou et al. (2019) and this thesis. The consensus set identified in this thesis (see Figure 6-12) did not include these activities, either as they were eliminated due to low AR rates or as statistical significance was not proven during the analysis. However, some of the gestures were suggested by participants during the elicitation. Table shows the matches between the gestures selected by Hou et al. (2019) and gestures proposed during the gesture elicitation performed in the research reported in this thesis.

Hou et al. (2019) found that the users preferred dynamic gestures, particularly for continuous gestures. This matches with the findings in this thesis, as static pose, the only static gesture type used, occurred 11 times (0.006% of the sample). Hou et al. (2019) also found that users "preferred gestures connected to real life with context logic" and that they adopted reversible gestures for dichotomous tasks. These statements also correspond to the findings in this thesis. Iconic gestures were still dominant with 73% of the sample, but pantomimic gestures, presumably miming equivalent physical activities, were identified in 26% of the sample. Regarding dichotomous gestures, 28 out of 57 gestures identified in the consensus set in this thesis (see Figure 6-12) did have a dichotomous counterpart.

Table 8-2 : Matching gestures identified between the studies by Hou et al. (2019) and the one reported in this thesis

Gesture chosen for the activity by (Hou et al., 2019)	**Same gesture proposed during the gesture elicitation study reported in this thesis**	**Gesture sketches**
Create a round	Drw14 was proposed by 8 participants to create a circle	
Create a square	Drw15 was proposed by 7 participants to create a rectangle	
Create a cube	Drw21 was proposed by one participant to create a cube	
Slice	Split05 was proposed by one participant to slice a part in half	
Delete	Undo01 was proposed by 7 participants, and selected as a preferred gesture for the activity when the excluded set was evaluated. However due to the low statistical significance it did not form the part of the consensus set. (note: undo does not have to be the same activity as delete, but for Undo01 it effectively was as the object was deleted as a consequence)	

Cultural factors potentially affecting gesture elicitations were out of the scope of this thesis. However, it must be mentioned that they likely exist and might be one of the reasons behind the differences in findings in this thesis and the studies it was compared to in this section. Studies have found that cultural influences tend be lower for “tasks strongly associated with direction and order”, “object manipulation”, “tasks dealing with objects that can be mapped to concrete objects in the real world” and “tasks associated with universally accepted symbols” (Wu et al., 2020). Activities for creation and manipulation of simple 3D objects shared between the work of Hou et al. (2019) typically can be mapped onto the “real world”, include object manipulation and are associated with direction. On the other hand, cultural norms tend to impact how many hands and fingers are involved in gesture and representation of abstract concepts dependent on the language and language patterns (Wu et al., 2020). This could explain the discrepancy in findings about the number of hands used between this thesis and findings by Khan and Tunçer (2019)

8.2.3. Consideration of legacy bias

Legacy bias, the effect established practices and habits in gesture use for similar or related activities using currently available technology has on gesture elicitation, was considered to be an important element in the methodology developed by Morris and Wobbrock. Morris et al. (2014) developed three methods, which can be used to reduce it - Production, Priming and Partners. Production requires the users to produce multiple interaction proposals for each referent, which may force them to move beyond the legacy influence. Priming provides an idea of possibilities the participants may want to consider, again aiming to disassociate their thinking from the established practices. Partners allows participants to work together and compare ideas.

Other authors believe legacy bias is not necessarily an issue, and that good legacy bias may help the participants remember the gestures e.g. turning a page of a physical book is similar to the swiping gesture used for e-books (Köpsel and Bubalo, 2015). They argue that legacy bias should be addressed by inventing different gestures only if they have proven to be problematic.

The work reported in this thesis does not explicitly consider legacy bias, as it was out of its scope, and participants were only asked to suggest one gesture at the time. However, in the first part of the study a number of gestures have been repeated for different referents, at different, randomised, times during the elicitation sequence. This was done, primarily, to establish whether the participants consistently suggested the same gestures for the same activities, and to explore the effect of referent shape on the gesture. However, it did have the added benefit of multiple gesture suggestions when the participants did not suggest the same gesture for the same activity consistently.

Looking at the gesture vocabulary compiled as a result, although the legacy bias was not explicitly considered it did not seem to be present in the elicited gestures. The only exception are limited number of gestures proposed for the zoom and select activity that resemble the gesture people perform to zoom on tablets and phones. It was hypothesised that low perceived levels of legacy bias were likely due to the unlimited space the participants could perform their gestures in and due to instructions given to them not tying them to any existing technology. However, participants have not been explicitly asked about this, and the hypothesis cannot be proven or rejected at this point.

8.2.4. Gesture evaluation

Morris et al. (2014) suggested that a good gesture should be discoverable, easy to perform, and easy to memorise or reliable.

The experiment design followed in the study this thesis reports had the requirement for gestures being easy to perform built in, as it was hypothesised that most frequently suggested gestures would have also been easy to perform, intuitively. This was confirmed through the evaluation reported in Chapter 7, as gestures were evaluated by the general public among other factors for ease of performance, and scored highly across the entire consensus set (all scores can be seen in Appendix H, Section H.2).

Gesture reliability would ultimately depend on the implementation modality and quality of the implemented solution, and this was not considered in the elicitation stage, other than observing the likelihood of participants using the same gesture for the same activity performed between different objects, which was discussed in Section 7.2. Three activities were tested for this (*Zoom in*, *Translate up*, and *Rotate cw*) and when three different objects were observed, out of 132 gestures for all three activities combined (irregular sphere, phone and chair), only 26 same gestures were performed for the same activity for all objects (20%) within participants. When the pool of observed activities was expanded to eight (*Zoom in/out*, *Rotate clockwise/counter clockwise*, and *Translate up/down/left/right*) and activities were observed for two different shapes (irregular sphere and the phone), out of 351 gestures for all of these activities combined, 123 same gestures were performed within participants (35%). This would indicate low reliability; however, as discussed in Section Figure 7-2 shape of an object seemed to have an effect on the reliability of the gesture repetition, making the repetition of the same gesture for different shapes an inappropriate indicator of reliability of gestures.

Gestures elicited in the study were suggested by participants from a theoretically unlimited pool of potential gestures, and significant agreement reached for majority of activities (68%). Further statistical analysis indicated the agreement did not happen by chance and there were commonalities between preferred gestures for the same activities between different designers. This implies that gesture discoverability may also be important, as different participants have “discovered” the same gestures, without knowledge of what others have done.

Ease for memorising would become indicative later in the implementation stages, and would only be considered if the system in development used prescribed gestures. It is envisaged by the researcher that the gesture systems of the future may not be entirely prescribed, and this will be further discussed in the future work in Section 8.3. Hence, ease for memorising was not considered further.

8.2.5. Consideration of statistical approaches

Over the past decade the statistical methodology used to analyse the frequency of gesture appearance has changed and improved, and Agreement Rate (AgR) is now frequently used for gesture elicitation (Vatavu and Wobbrock, 2015). Tsandilas (2018) argued that this was not enough, and that an additional metric establishing the likelihood of the effect being measure happening by chance was needed. This has been added to the methodology followed in the work reported on in this thesis and both AgR and Fleiss kappa were observed during the gesture analysis. However, there are still studies in the field where only number of repetitions of a gesture overall is observed (Khan and Tunçer, 2019).

While this is probably not enough to reliably claim that certain gestures are the preferred ones, it is also true that the statistical analysis itself would likely benefit from further exploration, as there were significant disagreements between the positions established authors in the field hold. For example, Vatavu and Wobbrock (2015) claimed that when the potential solution space is unlimited metrics establishing the likelihood of something happening by chance were not reliable. Tsandilas (2018) posited it was still better to use them then not. Study reported in this thesis was statistically analysed including both recommendations. This approach is repeatable and the results can be compared to the existing studies in the similar fields. However, work performed on improving the analysis metrics is continuous (Vatavu, 2019) and likely to improve as the field of gesture elicitation in the unlimited solution space grows.

8.2.6. Limitations

Research methodology design focused on providing as much freedom to the participants as possible. The goal of the study was to allow for the use of any gestures the participants found appropriate, performed intuitively and disregarding any limitations technology used for detection could introduce. However, choices made to support this approach also introduced some limitations to the process.

Participants could not see what they were creating live, so the paradigm used was not a true Wizard of Oz one. Therefore, it was possible they could forget steps they had already carried out in their mind. It is hypothesised by the author that if they could see the creation live more detail would be obtained on the use of gestures, and more manipulative gestures would occur (particularly in the Part 2 of the study).

In Part 1 of the study participants interacted with four objects. In Part 2 of the study participants interacted with three different objects. In Section 7.2, while testing the study robustness, the conclusion was reached that a shape of the object had an influence on the gestures performed. While observing the data showing the gestures that were not repeated frequently enough to be included in the consensus set, it was also noticed that the more complex the activity was more gestures seemed to convey the shape of the object or appear to interact with it more. If the study were to be repeated, a significantly larger number of objects of various sizes would have been included in both parts of the study, in order to further explore how object type influences gestures.

In Part 2 of the study (‘free creation’) agreement rates for gestures for the same activity were much lower than in the Part 1. It is likely that this was partially due to the lower number of same activities performed by different participants i.e. as the participants were free to choose their activities, a larger variation of different activities appeared, leading to lower number of repetitions for each of the activities. The author estimates that many more participants (~200) would be needed to see the repetition of gestures comparable to that of the Part 1 of the study. Additionally, it would have been beneficial to allow the participants to define what they found important in terms of gesture performance. For example, during the evaluation some participants stated that they would use tow hands only if objects were of certain size or if a specific level of accuracy was needed.

Half of the participants performed Part 1 of the study first, and the other half performed Part 2 of the study first. This was done to avoid effectively teaching the participants gestures for certain activities in Part 1 that they would use in Part 2 of the study. Following the completion of the study, it was realised that this has led to a different limitation. In Part 1 of the study participants were shown animations on a 2D screen and asked to imagine they were causing them and react to them using their hands to achieve the effect shown on the screen. No further guidance in terms of how the hands should be used or what they see should be perceived was given in order to record their intuitive and natural reaction. In Part 2 of the study participants were asked to imagine the object shown to them suspended in the space in front of them in 3D. They were also asked to imagine it had no weight and that gravity did not have an effect on it. In hindsight, the participants that performed the Part 2 of the study would have been primed to think in 3D prior to seeing the videos in the Part 1 for the first time. In the future, the author would reconsider the counterbalancing of conditions, as it is questionable if this has had a significant effect on the 3D perception during the Part 1 of the study. While priming half of the participants to perceive Part 1 of the study in 3D would not necessarily a negative effect, there may be a difference between the perceptions the two groups of participants while performing the activities in the Part 1 of the study.

The issue of 3D perception could have been avoided completely had the VR/AR technology been used for the representation. However, the use of VR/AR was problematic when participant recruitment was considered. Participants would have had to travel to a specialised facility, which would significantly increase the time they would need to dedicate to take part in the study and potentially significantly decrease the number of participants. Ability to recruit a high number of participants was deemed crucial to the effectiveness of the study, and as the pilot has shown that objects shown using 2D technology were perceived as 3D, VR/AR representation was not pursued. However, if it were possible to overcome the difficulty with technology access, VR/AR representation of the objects would have been preferred.

Gesture coding by humans is an inherently subjective and time-consuming process. While measures were taken to make it as objective as possible such as coding rules agreement between the three coders, and coding 10% of the sample for the categories that included most interpretation by all three coders, the subjectivity could not be removed entirely. The author would have preferred to apply an automated system for tracking and categorising gestures, to improve objectivity and reduce the analysis time, however it was not possible to develop one during the PhD term. This is further discussed as a topic for future work in Section 8.3.2.

8.3. Future work

Work reported in this study was performed using technology that is readily available and affordable at present, and implementing approaches proven and tested in the field of gesture elicitation for HCI. This field is evolving quickly, and it is highly probable that improved approaches will be adopted in the future. What these new approaches may be will be discussed in this section.

8.3.1. Influence of object shape, recognizability and size on gesture performance

Section 7.2 discussed the effect shape and recognisability of the object have on gestures performed by the participants. Shape was found to have an effect on the gesture performed. Recognisability also appeared to have an effect. However, it was suspected that the difference in shapes of the object might have influenced the participant's gestures regardless of the recognisability to an extent, as the recognisable objects used in this study, the phone and the chair, had very different shapes. During gesture analysis (in Section 6.3) it was noticed that gestures for *Bend*, *Sculpt*, *Multiply/Pattern, Loft* and *Undo* often took forms influenced by the shape of the object being manipulated or modified. At this stage, the focus of the research was to explore if shared gestures for conceptual design could be identified, and to create an initial vocabulary as a basis for a future research. Current findings were based on observation of three objects with different shapes, where one did not have a recognisable function and two did. In the future, a larger pool of objects of different shapes and recognisability levels could be included in the studies in order to further analyse how they influence the interaction.

In the physical world, generally, a chair is a larger object than a phone, and a generic sphere would typically not have an inferred size. The chair was initially added to the list of objects in order to test the interaction with another recognizable object of a different shape. The size of the object was discussed by some participants during evaluation of the consensus set while explaining how they might prefer a different gesture if they were interacting with a smaller or a larger object. While this was not initially planned, the collected data was analysed for similarity between gestures depending on the size of the object. If the perceived size of an object influenced the interaction with the object, it would be expected that a substantial proportion of gestures used to interact with a chair would be different from the gesture used to interact with the phone and the irregular sphere. Sixteen out of 132 interactions were the same regardless of the object's inferred size (12%). This may mean that the perceived size of an object might have an influence on the interaction type. This question was not posed in the questionnaire, as size was not planned to be observed, hence no comparison could be made between the participants' perception of their own activities and the performed activities. It does however pose an interesting question of if interaction with objects in virtual environments where scaling of the objects is easily achievable would still be influenced by the size of an object in the physical world, if the participant was familiar with it.

As this research primarily aimed to answer the question of if a common vocabulary for conceptual design can be identified, it included high-level shapes and excluded detail, and consideration of dimensions or proportions. While the nature of conceptual design is to deal with frequently changing, vague and not fully defined ideas, and develop them into concepts, it will also be necessary to explore how detail definition affects the gesture choices in the future work.

8.3.2. Automatic classification

While the approaches to gesture classification varied slightly between different studies, they were all still clustered manually by researchers analysing the studies (Vatavu, 2019). This is time consuming and can be an inherently unreliable process, although techniques such as interrater compatibility were applied to increase the likelihood of consistent coding practices. Additionally, elicitation studies relied on descriptive taxonomies, which could be interpreted in different ways by different coders.

There are already developments addressing this issue. Crowdsourced gesture research annotation of datasets, which can then be explored via a visualisation tool, was one of the proposed ways forward (Grijincu et al., 2014). Another approach was the development of an automated system that performs the analysis of gesture patterns. GestureAnalyser proposed by Jang et al. (2014) was using interactive clustering and visualisation techniques are applied to motion tracking data via the application of data mining techniques. Similar gestures from different users were identified as a gesture pattern. It could cluster gestures hierarchically, and observed 3D positions of 11 body joints (hands, elbows, shoulders, head, neck, chest and pelvis). So far it has been applied to mid-air gesture elicitation of gestures for camera view control in 3D space and music player control and it requires further development and higher integration of gesture taxonomies. Similar solution called Kinect Analysis was developed by (Nebeling et al., 2015). It supported recording, replay, visualisation and analysis of gestures detected using Kinect sensor. Its aim was to automate coding and analysis during gesture elicitation, and suggestion was that it could be used before the GestureAnalyzer, for the initial round of coding. Rules could be set based on position of joints, distance between skeleton and Kinect or between skeletons. It could also search for expressions in recorded speech or recognise predefined gestures. Tests have shown limited usability of this solution, and occasionally manual coding was still needed. However, overall development of tools for automatic analysis of in-air gestures was considered likely to be one of the future focuses in the field (Koutsabasis and Vogiatzidakis, 2019).

The future developments would benefit from a shared rule based taxonomy. Existing systems had their own taxonomies. Some overlapped with those found in the work of Wobbrock, Puimsonbon and Billingham. Others were general and simplified gestures too much, e.g. classify them as pinch, C shape, L shape even where much higher levels of variation were likely to have existed. Existing solutions were focusing on full body motions, and hand gestures require more fine detail. They require tracking of all hand joints instead of full body and a reliable way to classify similar motions, which may include less physical movement but more complexity.

The drawback of some of the existing systems was that they were relying on a specific recognition technology system e.g. Kinect Analysis (Nebeling et al., 2015) is Kinect reliant and Kinect has been discontinued. Cross-platform systems or cross-field standardisation practices would be highly beneficial.

8.3.3. Individualised gesture interfaces

The outcomes of the study resulted in a consensus set which was presented in Chapter 6 and following evaluation by the general public another variant of it was given in Chapter 7. However, these are not necessarily meant to be seen as a rigid prescribed set to be used exclusively in the future conceptual design systems. They are instead considered by the author as a potential first step towards a development of a system, which could adapt itself to the user. The identified vocabulary could be a starting point, a pre-set that could be built on. This base gesture vocabulary could be extended by performing studies where a variety of different objects are interacted with, in order to identify if additional gestures should be added to the set to cover the effects of object shape or recognisability. The intention of this thesis was to identify a gesture vocabulary for form creation, and it thus focused on designers for gesture elicitation. However, it could be argued that it may benefit from being extended by the gestures elicited from general population, as it might introduce more intuitive activities that have not been pre-learned through design education.

8.4. Summary

The aims and objectives set out in Section 4.4 have been met, and they have been met via application of established research techniques and methodologies, which were modified using, justified reasoning.

Strengths of the research reported in this thesis were:

- Large number of participants was included in the study (defined by reaching the saturation),
- Coding scheme was based on established taxonomy,
- Inter-coder reliability measures were in place,
- Statistical analysis applied was following the updated recommendations form the literature tackling similar research problems.

Then user evaluation by non-designer participants was performed confirming that resulting gestures consensus set comprises of were easy to use and appropriate.

Weaknesses were linked to the participant recruitment and scope of the work performed. Majority of main study participants were educated at the same institution following the same programme, and this may have contributed to the similarities in their behaviour. At this stage, the research focused on designing the shapes, which represent designers' ideas, but do not focus on sizes, dimensions or details. While these are usually not fully defined at the conceptual design stage, in some cases it may be crucial to indicate a specific constraint or a dimension either because it is functionally important or because it fundamentally defines the shape being created. These should be explored in future research.

Future research would also benefit from inclusion of a wider variety of distinct shapes, which are good representatives of larger shape groups, so that effect of shape, recognition and size of objects on the gestures could be further explored. Finally, some participants did not perform all of the activities in the stages where each step was not prompted. For example, in free design sequence some shapes were not fully “modelled”, and manipulation activities that would have likely occurred in reality were not performed by the participants, presumably due to lack of visual cues that would remind them they were needed.

While research approach, taxonomy used for coding, and steps followed during the analysis were largely adopted from the established practices employed in the field of research exploring user elicited gestures for HCI, they were adapted for use aiming to identify the most natural and intuitive gestures for conceptual design. Justifications for these changes were provided and discussed in this chapter.

The research approach could be improved in the future. Coding in this study, but also prevalent in the field of user-elicited gestures for HCI was typically performed manually by the researchers, which was a time consuming and inherently subjective process. While measures such as well-defined taxonomies and inter-rater reliability were taken to make the analysis process as consistent and repeatable as possible, introduction of automated coding would speed up the process and increase the reliability of the studies.

Finally, the consensus sets resulting from the work reported in this thesis are a good starting point for the vocabulary of gestures for conceptual design. In the future following further research, these might develop into a language for conceptual design. They are considered by the author to be a valid representation of gestures commonly used by designers. However, they were not meant to be used as a prescribed and unchangeable gesture set. The intention was to provide a vocabulary which is easily discoverable and adoptable by the future users, but that can evolve and improve over time, and perhaps even adapt itself to the user akin to predictive text assistance or handwriting recognition modern technology provides.

9. Conclusion

This thesis aimed to answer the question of "What gestures would designers use naturally and intuitively if they were not constricted by technology and the design process imposed on them by CAD architecture?" In order to answer it a gesture vocabulary of user-elicited gestures for design was developed, as a first step towards achieving a more natural and intuitive interaction with a system supporting conceptual design. Overall summary of the work, focusing on contributions is given in Figure 9-1.

To achieve this a number of objectives was set and completed in this thesis, and they will be briefly summarised in the remainder of this chapter.

Objective 1: Provide an overview of existing approaches to support for conceptual design via a literature review – Chapter 2 provided an overview of CAED, CAD and conceptual design. It found that conceptual design was not well supported by CAED/CAD, in large part due to disconnect between the nature of the conceptual design, where designs are vague, ill-defined and evolving, and computational systems requiring clear definitions and lacking ability to automate a process in which activities cannot always be predefined or predicted. Existing solutions supporting conceptual design were often guided by what was easily achieved using latest technology developments, rather than what was needed to better support the nature of the design process. Gesture based interfaces, or multimodal interfaces with gestures were identified as one of the possible modalities with potential to introduce a more intuitive way of working.

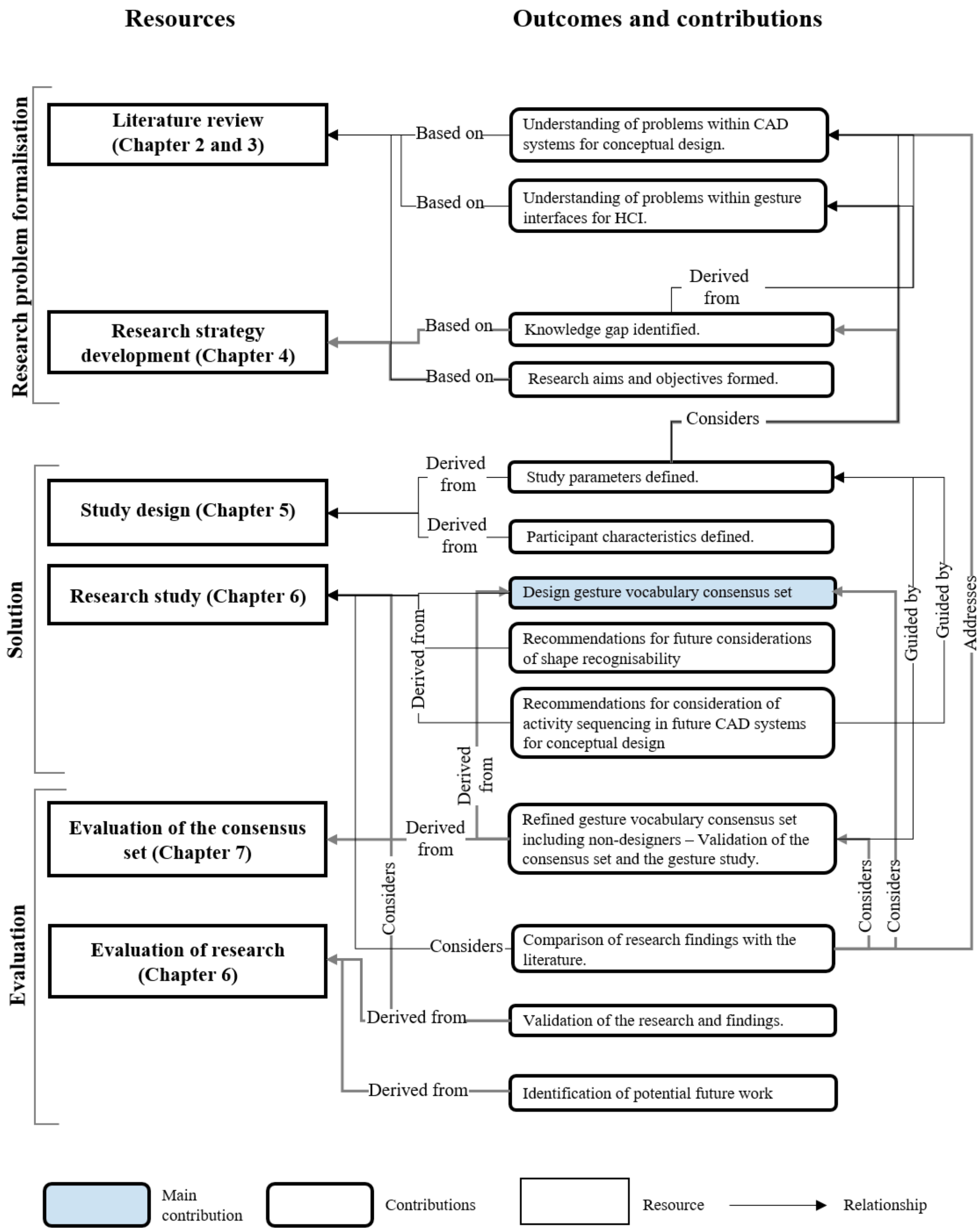


Figure 9-1 : Summary of work

Objective 2: Provide an overview of gesture use for applications focusing on design via a literature review - Chapter 3 provided an overview of the patterns of touchless hand gesture use in gesture interfaces. While gestures were frequently used as an interaction modality in interfaces developed for various purposes, they have not been explored, in depth, for design. In design applications, gestures used were either those prescribed by designers that were able to convey symbolic concepts, or free-form imitation gestures, which were suggested by users but typically unable to support symbolic concepts. Neither prescribed nor free-form gestures with limited applicability were the most conducive for the development of natural and intuitive systems which could support the conceptual design process, without interrupting or encumbering it. Additionally, users were found to prefer user elicited gestures to those defined by system designers. Design solutions utilising gestures for interaction were most frequently supported by sensing technology. The way gestures were used in the interfaces in relation to speech was also found to not be fully aligned with existing theories on gesture use for communicative purposes, and it was believed that this was often due to technical limitations.

Objective 3: Define a knowledge gap based on the outcomes of Objective 1 and Objective 2 – It was identified that if a gesture-based solution was to be used to support conceptual design, it was not known what gestures designers would use, if they were given no instructions and if there were no limitations. Existing limitations were imposed by the technology currently facilitating the systems supporting conceptual design, or the design process imposed on them by CAD architecture. To address this gap, a vocabulary of in-air hand gestures for conceptual design was to be identified that was isolated from current technology and elicited from designers. This was discussed further in Chapter 4.

Objective 4: Define the methodology that will be followed in the study performed to identify the vocabulary of hand gestures for conceptual design – Chapter 5 covered the chosen research approach. It was based on user based participatory design technique and taxonomies established in the HCI field of research, adapted to the needs of the natural and intuitive in-air gesture identification for conceptual design.

The two-part study design was successfully tested and refined via two pilot studies. Both parts of the study had the same set up. It was decided that the participants would watch referents on a screen, animations of activities in Part 1 of the study and images illustrating objects they were about to create in Part 2 of the study. They would be recorded, using two video cameras, as they used their hand gestures to emulate how they would achieve what they saw on the screen, as they were seeing it. The activities shown on the screen were designed to collect data on manipulative and modifying gestures, gestures for creation of shapes, and information on the sequence of activities chosen to create an object. The objects chosen for inclusion would be easily recognisable common products, or simple yet abstract shapes. Participants would be 3rd-5th year Product Design Engineering students or graduates, from University of Strathclyde and Glasgow University/Glasgow School of Art, and the data collection would continue until saturation was reached. The recordings would then be analysed; coded, classified, categorised and then statistically analysed (AR, Fleiss kappa, Chi Squared goodness of fit) by the author. Ten percent of the sample would first be coded by additional two coders in order to develop consistent coding rules and ensure agreement is reached between the three coders. This would be confirmed via the use of inter-coder reliability measures.

Objective 5: Perform the study and build the vocabulary of hand gestures for conceptual design – Chapter 6 reported the results of the study. Forty-four participants took part in the study. One thousand seven hundred and ninety two gestures were added to the data set, 1090 from Part 1 and 702 from Part 2 of the study. These were then parsed, sketched and coded based on the taxonomy defined in Chapter 5. Then they were categorised based on the hand form and the path travelled, in a number of categories and sub categories. Statistical analysis including combination of AR and Fleiss κ was used to determine which gestures should be added to the consensus sets for the gesture vocabulary for both parts of the study. Chi square analysis was then applied to the categories of gestures in order to determine the likelihood of number of repetitions for each category occurring by chance. Following Chi square analysis, those that were likely to have not been repeated by chance were retained in the consensus sets for Part 1 and Part 2, and merged into a unified consensus set. This consensus set represented the variants for 20 in-air gestures frequently used during conceptual design, and these are suggested to be used as a base for further development of a vocabulary for conceptual design in 3D space.

Objective 6: Evaluate the vocabulary of hand gestures for conceptual design – Consensus set and discarded set identified in the Chapter 6 were evaluated in the

Chapter 7. Evaluation had two parts, and evaluation participants were ten non-designers. Non-designers were chosen in order to test the appropriateness and ease of performance of gestures outside of the design community. They were also included to reduce bias that may have been introduced by the designers' education.

The first had a theoretical approach requiring users to emulate use of gestures while observing a photograph of the object they were meant to imagine interaction with. The second used a VR application that allowed participants to test the gestures in the VR environment. When more than one gesture variant was tested for a specific activity, participants were required to pick their preferred gesture. The gestures were rated for the appropriateness for the activity they were preforming and ease of gesture performance in both parts of the study, and the chosen gestures were rated highly for both. In the second part of the evaluation, two additional parameters were evaluated - satisfaction with the achieved result and the ease or difficulty of performance in the VR system.

Satisfaction with the achieved result was consistently high, but ease of performance in the application varied, due to technical difficulties during implementation influencing the VR system performance. However, it was found that majority of the participants were able to disassociate the gesture from the implementation issues. Preference for single-handed gestures was observed during evaluation, with majority of participants perceiving two-handed gestures as tiring and unnecessary. A variation of the consensus set was created as an outcome of the evaluation, taking into account the non-designers perspective. This provided an indication on what types of gestures the language for conceptual design might benefit from focusing on if it were to target wider audience than just professional designers.

Objective 7: Test the study robustness - While vocabulary of gestures for conceptual design was the primary goal of this thesis, two additional parameters where explored to test the study robustness that may inform development of future conceptual design support systems: The effect of the object shape and recognisability and the procedural sequence of gestures performed to create the objects. Gestures same participants performed for the completion of the same activities for different objects were observed to explore if shape or recognisability of the objects have an effect on the gesture performed.

Object shape was shown to likely have an effect on the gesture performance. The data indicated that recognisability might have an effect as well; however, as it was hard to separate recognisability from the object shape, this could not be claimed with certainty. The effect of the object shape was also noticeable for more complex modification activities such as *pattern* or *undo*, where the gesture performed was often not generic but closely linked to the shape of the object being modified. In the Part 2 of the study, procedural sequence of the activities was also observed. When the sequence was not guided, participants often diverged from the procedural sequence that would have been followed if the shape were to be created in a CAD system, and instead included sculpting or forming paradigms. This was particularly prominent when the shape created was more complex. For example if it did not have perpendicular angles or used standard shapes such as cube, sphere etc. It was concluded that further exploration of the best design process to follow would benefit potential future development of a conceptual design support system using in-air gestural interfaces.

Objective 8: Discuss research outcomes, its strengths and weaknesses and future work - Chapter 8 provides a discussion on research outcomes, strength, weaknesses and future work. Research outcomes were discussed by listing the research objectives and tasks and reporting the outcomes. Following the study and evaluation completion and data analysis, all tasks were addressed. The key outcomes were the consensus set of the gestures for conceptual design, and its variant evaluated by non-designers.

Strengths of the research include a large number of participants performing the study (defined by reaching the saturation), coding scheme that was based on established taxonomy, inter-code reliability measures put in place, statistical analysis applied following the updated recommendations form the literature tackling similar research problems, and user evaluation by non-designer participants confirming that resulting gestures consensus set comprises of were easy to use and appropriate.

Weaknesses were linked to the participant recruitment (majority educated at the same institution) and scope of the work performed (focus on designing the shapes which represent designers’ ideas, but no consideration of sizes, dimensions or details). Finally, a limited number of participants did not perform all of the activities in the stages where each step was not prompted.

Future research could focus on some of these weaknesses. For example, in the future a wider variety of distinct shapes that are good representatives of larger groups of shapes could be included, so that both effect of shape, recognition and size on gestures and gestures used for interaction with these objects that may be affected by their shape could be further explored. Coding in this, as well as in the similar studies, was typically performed manually by the researchers, which was a time consuming and inherently subjective process. Introduction of automated coding would speed up the process and increase the reliability of the studies.

Finally, the key outcomes of this thesis, the consensus sets of gestures for conceptual design, were not meant to be used as a prescribed and unchangeable gesture set. Instead, they were envisaged as a starting point for a language that could evolve and improve over time, and perhaps even adapt itself to the user akin to predictive text assistance or handwriting recognition modern technology provides. Extensive further work in multiple fields will be required to reach this point. However, the consensus sets resulting from this thesis are considered a valid representation of gestures commonly used by designers for form creation, manipulation and modification.

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User-based gesture vocabulary for form creation during a product design process – Appendices

by

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This dissertation is submitted for the degree of Doctor of Philosophy

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Table of Contents

Appendix A – Articles included in the gesture systematic review discussed in Chapter 3

This appendix provides additional information on each individual article represented in Figure 3-6 in the main body of the thesis (Section 3.4.2.). The specific article can be identified by matching the location of the bubbles in the Figure 1 and the Figure 2 (which match Figure 3-6). Then more information of each specific article can be found in the table in Section A.2.

A 1 Link between Figure 9 and the numbered articles

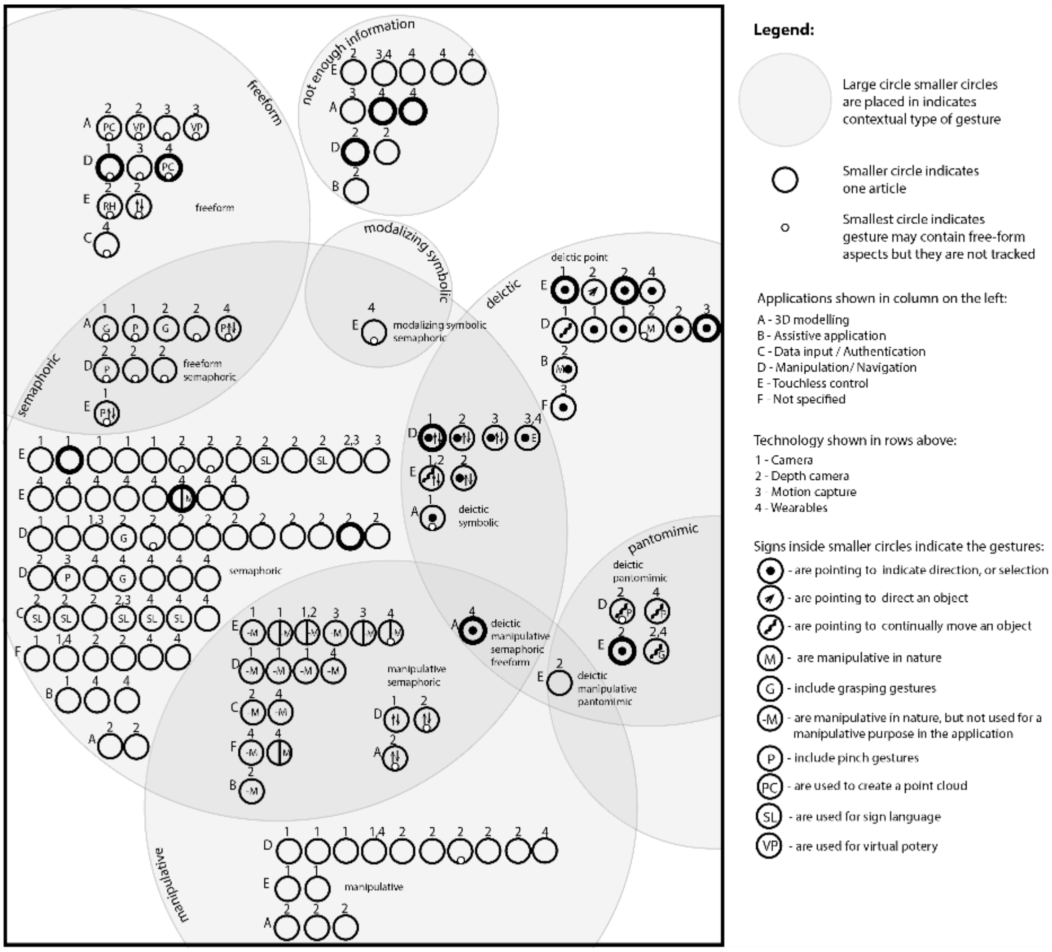

Figure 1 : Matching the visualised articles to the table in Section A.2 – location of the article in Figure 3-6

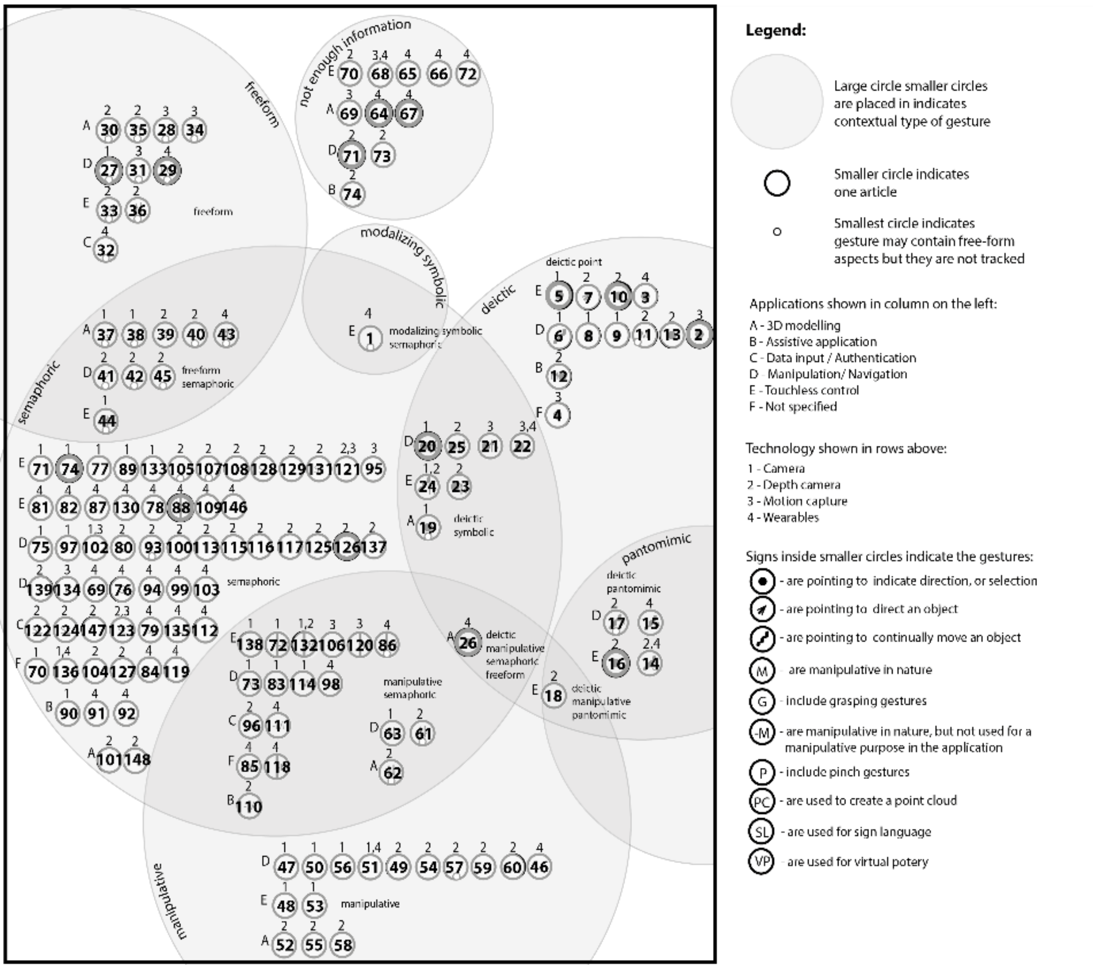

Figure 2 : Matching the visualised articles to the table in Section A.2 – numbering in the table

A 2 List of articles included in the review

Table 1 : Articles included in the systematic review of gesture interfaces Chapter 3 is based on

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
1	E. Lee, H. Kiel, S. Dedenbach, I. Grüll, T. Karrer, M. Wolf and J. Borchers	2006	ISymphony: An adaptive interactive orchestral conducting system for digital audio and video streams	D	Hand	Modalizing symbolic	Controlling the music recording	The digital baton	Not specified	n	y	y	n	y	Not specified	
2	R. A. Bolt	1980	“Put-that-there”: Voice and gesture at the graphics interface	D	Hand	Deictic	Interaction with a display/projection	Magnetic based space sensing cube	Not specified	Speech	y	n	n	n	Not specified	
3	P. K. Pook and D. H. Ballard	1996	Deictic human/robot interaction	D	Hand	Deictic	Robot control	Glove	Not specified	VR	y	n	n	n	Not specified	
4	J. Rekimoto	2001	Gesturewrist and gesturepad:	S	Arm; Hand	Deictic	Not specified	Capacitance sensing	Not specified	Accelerometer	y	n	n	n	Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
			Unobtrusive wearable interaction devices													
5	S. Carbini, L. Delphin-Poulat, L. Perron and J. E. Viallet	2006	From a Wizard of Oz experiment to a real time speech and gesture multimodal interface	D	Hand	Deictic	Game control	Camera (RBG, VGA, web)	HMM (Hidden Markov Models) algorithm	Speech; Mouse	y	n	n	n	14+20	
6	Y. Y. Pang, N. A. Ismail and P. L. Siang Gilbert	2010	A real time vision-based hand gesture interaction	D	Hand	Deictic	Navigation/Selection in an app	Camera (RBG, VGA, web); Integrated compass; Accelerometer	Library - OpenCV	n	y	n	n	n	Not specified	Questionable quality of information
7	M. Van Den Bergh, D. Carton, R. De Nijs, N. Mitsou, C. Landsiedel, K. Kuehnlenz, D. Wollherr, L. Van	2011	Real-time 3D hand gesture interaction with a robot for understanding directions from humans	D	Hand	Deictic	Robot control	Kinect camera	Library - OpenNI	n	y	n	n	n	Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
	Gool and M. Buss															
8	M. J. Reale, S. Canavan, L. Yin, K. Hu and T. Hung	2011	A multi-gesture interaction system using a 3-D iris disk model for gaze estimation and an active appearance model for 3-D hand pointing	D	Hand	Deictic	Navigation/Selection in an app	Camera (RBG, VGA, web)	Active appearance model (AAM)	Eye tracker, Hand pose/poistion tracker, Mouth opening/closing tracker	y	n	n	n	Not specified	
9	Y. Xie and R. Xu	2013	Natural Bare-Hand Interaction for Remote Operating Large Touch Screen	D	Hand	Deictic	Interaction with a display/projection	Camera (RBG, VGA, web); Integrated compass; Accelerometer	Original Algorithm	n	y	n	n	n	10	Questionable quality of information
10	R. G. Boboc, A. I. Dumitru and C. Antonya	2015	Point-and-Command Paradigm for Interaction with Assistive Robots	D	Arm	Deictic	Robot control	Kinect camera	DTW (dynamic time warping) algorithm	Speech	n	y	n	y	Not specified	
11	Carreira, M, Ting, Karine Lan Hing, Csobanka Petra,	2017	Evaluation of in-air hand gestures interaction for older people	D	Hand	Deictic	Navigation and selection in graphical user interfaces for older people	Kinect camera	Microsoft SDK	n	y				40	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
	Goncalves Daniel															
12	Osti F, Ceruti A, Liverani A, Cagliana G	2017	Semi-automatic design for disassembly strategy planning: an augmented reality approach	D	Hand	Deictic	Disassembly of a 3D model	LEAP motion controller	Original algorithm	Vizux Star 1200 XL glasses	y	y		y	Not specified	
13	Nicola S, Handrea F-L, Crisan-Vida M, Stoicu-Tivadar L	2017	DNA Encoding training using 3D gesture interaction	D	Hand	Deictic	Interaction with a display/projection	LEAP motion controller	Unity, C#	n	y	n	n	n	27 + 23	
14	J. Savage-Carmona, M. Billinghurst and A. Holden	1998	The VirBot: a virtual reality robot driven with multimodal commands	D	Hand	Deictic, Pantomimic	Robot control	Glove	Original Algorithm	VR	y	n	n	n	Not specified	Questionable quality of information
15	S. Foehrenbach, W. A. König, J. Gerken and H. Reiterer	2009	Tactile feedback enhanced hand gesture interaction at large, high-resolution displays	D	Hand	Deictic, Pantomimic	Interaction with a display/projection	Infrared camera; Markers; Glove	Not specified	Tactile feedback, glove, markers	y	n	n	n	20	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
16	L. Hoste and B. Signer	2013	SpeeG2: A speech- and gesture-based interface for efficient controller-free text input	D	Hand	Deictic, Pantomimic	Home appliance control	Kinect camera	Not specified	Speech	y	n	n	n	9	
17	M. Covarrubias, M. Bordegoni and U. Cugini	2015	A hand gestural interaction system for handling a desktop haptic strip for shape rendering	D	Hand	Deictic, Pantomimic	Manipulating objects in AR/VR/3D	LEAP motion controller	Unity 3D	Physical spline representation supported by - Desktop Haptic Strip for Shape Rendering (DHSSR), Arduino Leonardo Board	y	y	n	y	15	
18	R. Sodhi, I. Poupyrev, M. Glisson and A. Israr	2013	AIREAL: Interactive tactile experiences in free air	D	Hand	Deictic, Manipulative, Pantomimic	Game control	Depth camera	Not specified	AIREAL	y	n	n	n	Not specified	
19	C. Yuan	2005	Visual tracking for seamless 3D interactions in augmented reality	S	Finger	Deictic, Semaphoric	3D architectural urban planning	Camera (RBG, VGA, web)	Colour segmentation	VR glasses	m	y	n	y	Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
20	E. H. C. Choi, R. Taib, Y. Shi and F. Chen	2007	Multimodal user interface for traffic incident management in control room	D	Hand	Deictic, Semaphoric	Interaction with augmented reality	Camera (RBG, VGA, web)	Colour segmentation, Rule Induction algorithm	Speech	y	n	n	n	8	
21	G. Lu, L.-k. Shark, G. Hall and U. Zeshan	2012	Immersive manipulation of virtual objects through glove-based hand gesture interaction	D	Hand	Deictic, Semaphoric	Interaction with augmented reality	A hybrid inertial and ultrasonic tracking system; Glove	Original Algorithm	Stereoscopic system	y	n	n	n	Not specified	
22	Y. Kim and J. Park	2014	Study on interaction-induced symptoms with respect to virtual grasping and manipulation	D	Hand	Deictic, Semaphoric	Manipulating objects in AR/VR/3D	Glove; Magnetic hand position tracker (Polhemus FASTRAK)	Not specified	VR	y	n	n	n	6	
23	M. Denkowski, K. Dmitruk and L. Sadkowski	2015	Building Automation Control System driven by Gestures	D	Hand	Deictic, Semaphoric	Home appliance control	Kinect camera; ASUS Xtion	Library - NiTE, OpenNI	n	y	n	n	n	12	
24	H.-s. Yeo, B.-g. Lee and H. Lim	2015	Hand tracking and gesture recognition system for human-computer interaction	D	Hand	Deictic, Semaphoric	Game control; 3D object manipulation	Depth camera; Camera (RGB,	Finite State machine and Kalman filter	n	y	n	n	n	Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
			using low-cost hardware					VGA, web)								
25	Lopes D S, Parreira P D de F et al	2017	On the utility of 3D hand cursors to explore medical volume datasets with a touchless interface	D	Hand	Deictic, Semaphoric	Medical applications	Kinect camera	Unity, Kinect SDK	n	y				22	
26	C.-C. P. Chu, T. H. Dani and R. Gadh	1997	Multi-sensory user interface for a virtual-reality-based computer aided design system	D	Hand	Deictic, Semaphoric, Manipulative, Free form	CAD manipulation	Glove	Not specified	VR, Speech, Gaze, haptics	y	n	n	n	21	
27	A. Wilson and N. Oliver	2003	GWindows: robust stereo vision for gesture-based control of windows	D	Hand	Free form	Navigation/Selection in an app	Camera	Original algorithm	Speech	n	y	n	y	18	
28	S. Qin, D. K. Wright, J. Kang and P. A. Prieto	2006	Use of three-dimensional body motion to free-form surface design	D	Hand	Free form	CAD manipulation; CAD Design	Markers; Eagle Digital Cameras	EVaRT 4.4 software to collect motion data	n	n	y	n	y	Not specified	
29	K. Moustakas, G. Nikolakis	2009	3D content-based search using sketches	D	Hand	Free form	Manipulating objects in AR/VR/3D	Glove; Camera (RBG,	Not specified	Force feedback	n	y	n	y	17	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
	, D. Tzovaras, S. Carbini, O. Bernier and J. E. Viallet							VGA, web)		device, Speech						
30	C. Holz and A. Wilson	2011	Data miming: inferring spatial object descriptions from human gesture	D	Hand	Free form	CAD design	Kinect camera	Not specified	n	n	y	n	y	15	
31	G. Beyer and M. Meier	2011	Music Interfaces for Novice Users: Composing Music on a Public Display with Hand Gestures	D	Hand	Free form	Interaction with a display/projection	Optical tracking system	Original algorithm	Display	n	y	n	y	21	
32	J. Guerra-casanova, C. Sánchez-Ávila, G. Bailador and A. de Santos Sierra	2012	Authentication in mobile devices through hand gesture recognition	D	Hand	Free form	Authentication	Accelerometer	Not specified	Phone	y	n	y	n	100	
33	P. Gil, C. Mateo and F. Torres	2014	3D Visual Sensing of the Human Hand for the Remote Operation of a Robotic Hand	D	Hand	Free form	Robot control	Kinect camera	Original Algorithm; Library - PCL (Point Cloud Library),	n	Not specified	y	n	y	3	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
									ROS (Robot Operating System)							
34	Y. C. Han and B.-j. Han	2014	Virtual pottery: a virtual 3D audiovisual interface using natural hand motions	D	Hand	Free form	Virtual pottery	Kinect camera; Optitrack motion-capture tracking system (with glove)	Not specified	Glove	n	y	n	y	Not specified	
35	Vinayak and K. Ramani	2015	A gesture-free geometric approach for mid-air expression of design intent in 3D virtual pottery	D	Hand	Free form	Virtual pottery	LEAP motion controller and SoftKinetic DS325 sensor, in two different experiments	Original Algorithm	n	n	y	n	y	15	
36	Kim S K, Kirchner E A, Stefes A, Kirchner F	2017	Intrinsic interactive reinforcement learning - Using error-related potential for real work human-robot interaction	D	Hand	Free-form, Manipulative	Robot control	LEAP	Original algorithm	EEG	y	y	y	n	7	
37	V. Buchmann, S. Violich,	2004	FingARtips: gesture based direct manipulation in Augmented Reality	D	Hand	Free form, Semaphoric	3D architectural urban planing	Camera	Original algorithm; Library	Glove; HMD; Haptics	y	y		y	Many users in an event	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
	M. Billinghurst and A. Cockburn															
38	H. Kim, G. Albuquerque, S. Havemann and D. W. Fellner	2005	Tangible 3D: Hand Gesture Interaction for Immersive 3D Modelling	S; D	Hand	Free form, Semaphoric	CAD manipulation; CAD design	Camera	Not specified	Polarized glasses	y	y		y	Not specified	
39	Vinayak, S. Murugappan, H. Liu and K. Ramani	2013	Shape-It-Up: Hand gesture based creative expression of 3D shapes using intelligent generalized cylinders	D	Hand	Free form, Semaphoric	CAD manipulation; CAD design	Kinect camera	Original Algorithm; Library - openNI	n	y	?		?	Not specified	
40	S. Arroyave-Tobón, G. Osorio-Gómez and J. F. Cardona-McCormick	2015	AIR-MODELLING: A tool for gesture-based solid modelling in context during early design stages in AR environments	D	Hand	Free form, Semaphoric	CAD design	Kinect camera	Original Algorithm; Library - for body tracking NITETM	HMD, WiiMote/Remote	y	y	n	y	21	
41	M. Kim and J. Y. Lee	2016	Touch and hand gesture-based interactions for directly manipulating 3D	D	Hand	Free form,	Interaction with	LEAP	SDK	n	y	y		y	3	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
			virtual objects in mobile augmented reality			Semaphoric	augmented reality									
42	G. Lee, D. Shin and D. Shin	2016	Mouse operation on monitor by interactive analysis of intuitive hand motions	D	Hand	Free form, Semaphoric	Navigation/Selection in an app	Kinect	SDK	n	y	y		y	Not specified	
43	G. Robinson, J. M. Ritchie, P. N. Day and R. G. Dewar	2007	System design and user evaluation of Co-Star: An immersive stereoscopic system for cable harness design	D	Hand; Upper body	Free-form, Semaphoric	Cable harness design	Glove	Not specified	HMD	y	y	n	y	10	
44	M. I. Boulabiar, T. Burger, F. Poirier and G. Coppin	2011	A low-cost natural user interaction based on a camera hand-gestures recognizer	Not specified	Not specified	Free-form, Semaphoric	Home appliance control	PS3Eye low cost camera	Library - OpenCV	n	y	y	n	y	Not specified	Questionable quality of information

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
45	Togootogtokh E, Shih T K, Kumara W G C W, Wu S, Sun S, Chang H	2018	3D finger tracking and recognition image processing for real-time music playing with depth sensors	D	Hand	Free-form, Semaphoric	Interaction and manipulation with different representation types	LEAP and Senz3D	Neural network (NN), model based and appearance based hand tracking	n	y	y	n	n	Not specified	
46	T. G. Zimmerman, J. Lanier, C. Blanchard, S. Bryson and Y. Harvill	1987	A hand gesture interface device	D	Hand	Manipulative	Manipulating objects in AR/VR/3D; Clinical hand impairment measurement tool	Glove			n	y	n	y	Not specified	
47	R. O'Hagan, A. Zelinsky and S. Rougeaux	2002	Visual gesture interfaces for virtual environments	D	Hand	Manipulative	Manipulating objects in AR/VR/3D	Camera	Colour segmentation	VR	y	n		n	Not specified	
48	M. Roccetti, G. Marfia and A. Semeraro	2012	Playing into the wild: A gesture-based interface for gaming in public spaces	D	Hand	Manipulative	Game control	Camera	Original algorithm; Library	n	y				Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
49	M. Riduwan, A. H. Basori and F. Mohamed	2013	Finger-based Gestural Interaction for Exploration of 3D Heart Visualization	D	Finger	Manipulative	Navigation/Selection in an app	Kinect camera	Original Algorithm; Library - OpenNI, NITE	n	y	n		n	Not specified	Questionable quality of information
50	H. Bai, L. Gao, J. El-Sana and M. Billinghurst	2013	Free-hand interaction for handheld augmented reality using an RGB-depth camera	D	Hand	Manipulative	Interaction with augmented reality	RGB-D camera	Library - OPIRA natural gesture tracking	Tablet	y	n	n	n	Not specified	
51	W. Hürst and C. van Wezel	2013	Gesture-based interaction via finger tracking for mobile augmented reality	D	Hand	Manipulative	Manipulating objects in AR/VR/3D	Camera (RBG, VGA, web); Integrated compass; Accelerometer	Qualcomm Augmented Reality (QCAR) SDK.	Markers	y	n	n	n	18+24	
52	J. Song, S. Cho, S.-Y. Baek, K. Lee and H. Bang	2014	GaFinC: Gaze and Finger Control interface for 3D model manipulation in CAD application	D	Finger	Manipulative	CAD manipulation	Kinect camera	Not specified	Gaze tracker	y	n		n	8	
53	N. H. Dardas, J. M. Silva and A. El Saddik	2014	Target-shooting exergame with a hand gesture control	D	Hand	Manipulative	Game control	Camera (RBG, VGA, web)	Bag-of-features and Support Vector Machine	n	y	n		n	15	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
									(SVM) algorithm							
54	R. Al-Sayegh and C. Makatsoris	2015	Vision-Augmented Molecular Dynamics Simulation of Nanoindentation	D	Hand	Manipulative	Manipulating objects in AR/VR/3D	Kinect camera	Not specified, different software	n	y	n	n	n	Not specified	
55	A. K. Noor and R. Aras	2015	Potential of multimodal and multiuser interaction with virtual holography	D	Hand	Manipulative	CAD manipulation	Kinect camera	Original Algorithm; Library - C++based SDKs, Unity plugins	VR	y	n		n	Not specified	
56	Wang, K.R, Xiao, B.J, Xia, J.Y, Li, Dan, Luo, W.L.	2016	A real-time vision-based gesture interaction system for virtual EAST	D	Hand	Manipulative	Interaction with a large screen	Web camera	CB (codebook algorithm), Open CV, Elliptical boundary model	n	y	n	n	n	14	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
57	Vosinakis, S, Koutsabasis, P	2018	Evaluation of visual feedback techniques for virtual grasping with bare hands using Leap Motion and Oculus Rift	D	Hand	Manipulative	Manipulating objects in AR/VR/3D	LEAP	Not specified	HMD	y				32	
58	Xiao Yu, Peng Qingjin	2017	A hand gesture-based interface for design review using leap motion controller	D	Hand	Manipulative	3D Modelling	LEAP	Original algorithm	VR	y	n	n	n	14	
59	Dondi P, Lombardi L, Rocca I, Malagodi M, Licchelli M	2018	Multimodal workflow for the creation of interactive presentations of 360 spin images of historical violins	D	Hand	Manipulative	Interaction and manipulation with different representation types	Kinect camera	Not specified	N	y	n	n	n	22	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
60	Park Kyeong-Beom, Lee Jae Yeaol	2018	New design and comparative analysis of smartwatch metaphor-based hand gestures for 3D navigation in mobile virtual reality	D	Hand	Manipulative	Interaction and manipulation with different representation types	LEAP	Not specified	HMD	y	n	n	y	15+15	
61	F. Hernoux and O. Christmann	2015	A seamless solution for 3D real-time interaction: design and evaluation	D	Hand	Manipulative, Semaphoric	Interaction with augmented reality	Kinect camera	Original Algorithm; Library - openCV, openNI	n	y	y		y	20	
62	N. Beattie, B. Horan and S. McKenzie	2015	Taking the LEAP with the Oculus HMD and CAD - Plucking at thin Air?	D	Hand	Manipulative, Semaphoric	CAD manipulation	LEAP motion controller	Not specified	HMD	y	y		y	5-10000	
63	J. Shim, Y. Yang, N. Kang, J. Seo and T.-d. Han	2016	Gesture-based interactive augmented reality content authoring system using HMD	D	Hand	Manipulative, Semaphoric	Interaction with augmented reality	RGB-D camera	Library - OpenCV, OpenNI	HMD	y	n		n	28	
64	T. H. Dani and R. Gadh	1997	Creation of concept shape designs via a virtual reality interface	D	Hand	Not enough information	CAD Design	Glove	Built in glove tracker	VR, Speech	y	n	n	n	Not specified	

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65	Z. Xu, C. Xiang, W.-H. Wang, J.-H. Yang, V. Lantz and K.-Q. Wang	2009	Hand gesture recognition and virtual game control based on 3D accelerometer and EMG sensors	D	Hand	Not enough information	Game control	EMG; Accelerometer	HMM (Hidden Markov Models) algorithm	n	y	n	n	n	5	
66	M. Schreiber, M. Von Wilamowitz-Moellendorff and R. Bruder	2009	New interaction concepts by using the wii remote	Not specified	Not specified	Not enough information	Home appliance control	Accelerometer	HMM (Hidden Markov Models) algorithm	WiiMote/Remote	y	n	n	n	30	Questionable quality of information
67	P. Bourdot, T. Convard, F. Picon, M. Ammi, D. Touraine and J. M. Vézien	2010	VR–CAD integration: Multimodal immersive interaction and advanced haptic paradigms for implicit edition of CAD models	D	Hand	Not enough information	CAD manipulation	Glove, Wand, EVI3d	EVI3d software	Speech; VR	Not specified	Not specified	n	n	Not specified	
68	M. Chen, G. AlRegib and B.-H. Juang	2011	An integrated framework for universal motion control	D	Hand	Not enough information	Game control	Accelerometer; World Viz PPT-X4 optical	Not specified	WiiMote/Remote	y	n	n	n	Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
								tracking system								
69	J. Kang, K. Zhong, S. Qin, H. Wang and D. Wright	2013	Instant 3D design concept generation and visualization by real-time hand gesture recognition	D	Hand	Not enough information	CAD manipulation; CAD design	Markers; Eagle Digital Cameras	HMM (Hidden Markov Models) algorithm	n	y	n	n	n	Not specified	
70	F. Lauber, C. Bottcher and A. Butz	2014	You've got the look: Visualizing infotainment shortcuts in head-mounted displays	D	Hand	Not enough information	Interaction with car controls	LEAP motion controller	Not specified	Button	y	n	n	n	37	
71	F. Fuhrmann and R. Kaiser	2014	Multimodal interaction for future control centers: An interactive demonstrator	D	Hand	Not enough information	Navigation/Selection in an app	Kinect camera; Leap motion sensor	Not specified	Screen; Speech	Not specified	Not specified	n	n	Not specified	
72	Z. Lv, A. Halawani, S. Feng, S. Ur Réhman and H. Li	2015	Touch-less interactive augmented reality game on vision-based wearable device	D	Hand	Not enough information	Game control	Google Glass or Phone mounted on a framework on an arm or a foot	Library - Android SDK/NDK, OpenCV	Google Glass; Phone	y	n	n	n	15	

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73	H. S. Adeen, A. Atia, A. Amin, A. Victor, A. Essam, E. Gharib and M. Hussien	2015	RemoAct: Portable Projected Interface with Hand Gesture Interaction	D	Hand	Not enough information	Interaction with a display/projection	Kinect camera	Uni-stroke and Protractor processing algorithms; Support Vector Machine (SVM) algorithm	Pocket projector	y	n	n	n	10	
74	Ojeda-Castelo, J.J, Piedra-Fernandez, J.A, Iribarne, L, Bernal-Bravo, C	2018	KiNEEt: application for learning and rehabilitation in special educational needs	D	Hand, Arm	Not enough information	Rehabilitation and learning in special education	Kinect	Original algorithm, Kinect SDK	Screen	y				7	
75	T. Baudel and M. Beaudouin-Lafon	1993	Charade: remote control of objects using free-hand gestures	D	Hand	Semaphoric	Navigation/selection in an app	Glove	Rubine's algorithm		y	n		n	10	
76	F. K. H. Quek	1995	Eyes in the interface	D	Hand	Semaphoric	No specific application yet	Hi8 camera	Was not applied	n	y	n		n	Not tested yet	
77	S. Waldherr, R. Romero	2000	A gesture based interface for human-robot interaction	S and D	Arm	Semaphoric	Robot control	Camera	Viterbi algorithm		y	n		n	4	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
	and S. Thrun															
78	T. W. Fong, F. Conti, S. Grange and C. Baur	2001	Novel interfaces for remote driving: gesture, haptic, and PDA	D	Arm; Hand	Semaphoric	Robot control	Camera	Library		y	n		n	Not specified	
79	D. M. Krum, O. Omoteso, W. Ribarsky, T. Starner and L. F. Hodges	2002	Speech and gesture multimodal control of a whole Earth 3D visualization environment	D	Hand; Finger	Semaphoric	Navigation/Selection in an app	Camera		Infrared	y	n		n	6	
80	O. Rogalla, M. Ehrenmann, R. Zollner, R. Becher and R. Dillmann	2002	Using gesture and speech control for commanding a robot assistant	D	Hand	Semaphoric	Robot control	Camera	Colour segmentation	Speech	y	n		n	12	
81	J. R. New, E. Hasanbelliu and	2003	Facilitating user interaction with complex systems via	D	Hand	Semaphoric	Manipulating objects in AR/VR/3D	Camera	Original Algorithm; Library		y	n		n	Not specified	

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	M. Aguilar		hand gesture recognition													
82	M. Deller, A. Ebert, M. Bender and H. Hagen	2006	Flexible gesture recognition for immersive virtual environments	D	Hand	Semaphoric	Manipulating objects in AR/VR/3D	Glove	Not specified	VR	y	n		n	Several users	
83	M. Hasanuzzaman, T. Zhang, V. Ampornaramveth and H. Ueno	2006	Gesture-based human-robot interaction using a knowledge-based software platform	Not specified	Not specified	Semaphoric	Robot control	Camera (RBG, VGA, web)	Not specified	Face recognition for person identification	not specified	not specified		n	7	Questionable quality of information
84	J. Kela, P. Korpipää, J. Mäntyjärvi, S. Kallio, G. Savino, L. Jozzo and M. Sergio Di	2006	Accelerometer-based gesture control for a design environment	D	Hand	Semaphoric	Home appliance control and CAD manipulation	Accelerometer	HMM (Hidden Markov Models) algorithm	Button	y	partially	y	n	37+15	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
85	N. Adamo-Villani, J. Heisler and L. Arns	2007	Two gesture recognition systems for immersive math education of the deaf	D	Hand	Semaphoric	Sign Language Input	Glove	Library		y	n		n	5	
86	S. Reifinger, F. Wallhoff, M. Ablassmeier, T. Poitschke and G. Rigoll	2007	Static and dynamic hand-gesture recognition for augmented reality applications	D	Hand	Semaphoric	Interaction with augmented reality	Infrared camera	HMM (Hidden Markov Models)	HMD	y	n		n	15	
87	L. Kratz, M. Smith and F. J. Lee	2007	Wiizards: 3D gesture recognition for game play input	D	Hand	Semaphoric	Game control	Accelerometer	HMM (Hidden Markov Model)	Accelerometer	y				7	
88	D. Bannach, O. Amft, K. S. Kunze, E. A. Heinz, G. Troster and P. Lukowicz	2007	Waving real hand gestures recorded by wearable motion sensors to a virtual car and driver in a mixed-reality parking game	D	Hand	Semaphoric	Game control	Glove	Original algorithm	Accelerometer; Gyroscope	y				2	

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89	J. P. Wachs, H. I. Stern, Y. Edan, M. Gillam, J. Handler, C. Feied and M. Smith	2008	A gesture-based tool for sterile browsing of radiology images	D	Hand	Semaphoric	Navigation/Selection in an app	Camera	Not specified	n	y	n		n	10	
90	G. Niezen and G. P. Hancke	2008	Gesture recognition as ubiquitous input for mobile phones	D	Hand	Semaphoric	No specific application yet	Accelerometer	DTW (dynamic time warping) algorithm	n	y	n		n	10	
91	Z. He, L. Jin, L. Zhen and J. Huang	2008	Gesture recognition based on 3D accelerometer for cell phones interaction	D	Hand	Semaphoric	Not specified	Accelerometer	SVM (Support Vector Machine)	Phone	y	n		n	67	
92	J. Kim, S. Mastnik and E. André	2008	EMG-based hand gesture recognition for realtime biosignal interfacing	D	Hand	Semaphoric	Robot control	EMG	KNN algorithm (K-nearest neighbor)	n	y	y		?	30	
93	J. Liu, L. Zhong, J. Wickramasuriya and V. Vasudevan	2009	uWave: Accelerometer-based personalized gesture recognition and its applications	D	Hand	Semaphoric	Home appliance control	Accelerometer	Library - uWave	WiiMote/Remote; Button	y	partially	y	n	8+25+25	

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94	G. Pan, J. Wu, D. Zhang, Z. Wu, Y. Yang and S. Li	2010	GeeAir: a universal multimodal remote control device for home appliances	D	Hand	Semaphoric	Home appliance control	Accelerometer	FDSVM algorithm	WiiMote/Remote, eight-orientation joystick, built-in microphone, a speaker, buttons (for start and end of gesture), a built in digital signal processing unit	y	n		n	Not specified	
95	M.-y. Chen, L. Mummert, P. Pillai, A. Hauptmann and R. Sukthankar	2010	Controlling your TV with gestures	D	Hand	Semaphoric	Home appliance control	Camera	SVM (Support Vector Machine)	n	y				1	
96	M. Bhuiyan and R. Picking	2011	A gesture controlled user interface for inclusive design and evaluative study of its usability	D	Hand; Arm	Semaphoric	Assistive application	Camera	Not specified	n	y				70	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
97	C. Zhu and W. Sheng	2011	Wearable sensor-based hand gesture and daily activity recognition for robot-assisted living	D	Hand	Semaphoric	Assistive application; Robot control	Inertial sensor	HMM (Hidden Markov Model)	Phone	y				Not specified	
98	K. Nazemi, D. Burkhardt, C. Stab, M. Breyer, R. Wichert and D. W. Fellner	2011	Natural Gesture Interaction with Accelerometer-Based Devices in Ambient Assisted Environments	D	Hand	Semaphoric	Elderly users interface	Accelerometer	Not specified	WiiMote/Remote	y	n	y	n	26	Questionable quality of information
99	M. Wright, C.-J. Lin, E. O'Neill, D. Cosker and P. Johnson	2011	3D gesture recognition: an evaluation of user and system performance	D	Hand	Semaphoric	Manipulating objects in AR/VR/3D	Depth camera	HMM (Hidden Markov Model)	n	y	y		?	18	
100	T. Ni, D. A. Bowman, C. North and R. P. McMahan	2011	Design and evaluation of freehand menu selection interfaces using tilt and pinch gestures	D	Hand	Semaphoric	Navigation/Selection in an app	Glove	Original Algorithm	n	y	n		n	12	

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101	A. Mahr, C. Endres, C. Muller and T. Schneeberger	2011	Determining human-centered parameters of ergonomic micro-gesture interaction for drivers using the theater approach	D	Finger	Semaphoric	Interaction with car controls	Geremin	Original Algorithm; DTW (dynamic time warping) algorithm	n	y	n	?	n	24	
102	T. Cha and S. Maier	2012	Eye gaze assisted human-computer interaction in a hand gesture controlled multi-display environment	S	Hand	Semaphoric	Computer input	Infrared camera	Pixel recognition	Eye tracker	y	n		n	Not specified	Questionable quality of information
103	J. R. Cauchard, M. Fraser, T. Han and S. Subramanian	2012	Steerable projection: exploring alignment in interactive mobile displays	D	Hand	Semaphoric	Interaction with a display/projection	Camera (RBG, VGA, web)	Colour segmentation; Library - OpenCV	Pico-projector	y	n		n	Not specified	
104	P. Asadzadeh, L. Kulik and E. Tanin	2012	Gesture recognition using RFID technology	D	Hand; Arm	Semaphoric	Interaction with a display/projection	Skye-Module M9 UHF reader from SkyeTek (RFID) and their linear broadband UHF antennas.	Original Algorithm	RFID	y	n		n	120 samples	

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105	J. Lin, H. Nishino, T. Kagawa and K. Utsumiya	2012	A method of two-handed gesture interactions with applications based on commodity devices	D	Hand	Semaphoric	Navigation/Selection in an app	Accelerometer	Not specified	WiiMote/Remote; Sound; Vibration	y	n		n	10	Questionable quality of information
106	G. C. S. Ruppert, L. O. Reis, P. H. J. Amorim, T. F. de Moraes and J. V. L. da Silva	2012	Touchless gesture user interface for interactive image visualization in urological surgery	D	Hand	Semaphoric	Navigation/Selection in an app	Kinect	Library	n	y	n		n	Not specified	Questionable quality of information
107	D. Dave, A. Chowriappa and T. Kesavadas	2013	Gesture interface for 3d cad modelling using kinect	D	Hand; Arm; Upper body	Semaphoric	Virtual pottery	Kinect	SDK	n	y	n		n	13	

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108	A. Colaço, A. Kirmani, H. S. Yang, N.-W. Gong, C. Schmandt and V. K. Goyal	2013	Mime: compact, low power 3D gesture sensing for interaction with head mounted displays	D	Hand	Semaphoric	Navigation/Selection in an app	Time of Flight; Camera	Original algorithm	HMD	y	n		n	3	
109	T. Djukic, V. Mandic and N. Filipovic	2013	Virtual reality aided visualization of fluid flow simulations with application in medical education and diagnostics	S	Hand	Semaphoric	Manipulating objects in AR/VR/3D	Glove	Vizard VR Toolkit	VR	y	n		n	Not specified	Questionable quality of information
110	J. M. Palacios, C. Sagües, E. Montijano and S. Llorente	2013	Human-Computer Interaction Based on Hand Gestures Using RGB-D Sensors	D	Hand	Semaphoric	No specific application yet	Microsoft Asus Xtion Pro Live.	Original Algorithm	n	y	n		n	9	

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111	F. Garzotto and M. Valoriani	2013	Touchless gestural interaction with small displays: A case study	D	Hand; Upper body	Semaphoric	Home appliance control	Kinect camera	Library	n	y	y		y	Not specified	
112	M. Takahashi, M. Fujii, M. Naemura and S. i. Satoh	2013	Human gesture recognition system for TV viewing using time-of-flight camera	D	Hand	Semaphoric	Home appliance control	Time of Flight	SVM (Support Vector Machine)	n	y				20	
113	A. Riener, A. Ferscha, F. Bachmair, P. Hagmuller, A. Lemme, D. Muttenthaler, D. Puhringer, H. Rogner, A. Tappe and F. Weger	2013	Standardization of the in-car gesture interaction space	D	Finger; Hand	Semaphoric	Interaction with car controls	Kinect camera	Original Algorithm	n	n	y		y	12	

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114	R. Kajastila and T. Lokki	2013	Eyes-free interaction with free-hand gestures and auditory menus	D	Hand	Semaphoric	Interaction with car controls	Kinect camera	Original Algorithm; Library - OpenCV, OpenFrameworks, and OpenNi	Auditory menu	y	n		n	15	
115	J. Wu, G. Qiao, J. Zhang, Y. Zhang and G. Song	2013	Hand Motion-Based Remote Control Interface with Vibrotactile Feedback for Home Robots	D	Hand	Semaphoric	Robot control	Accelerometer	Not specified	n	y	n		n	1	
116	É. Rodrigues, M. Carreira and D. Gonçalves	2014	Developing a Multimodal Interface for the Elderly	D	Hand	Semaphoric	Elderly users interface	Kinect camera	Not specified	n	y	n		n	Not specified	Questionable quality of information
117	M. Yamada, J. Shan, K. Sakai, Y. Murase and K. Okabayashi	2014	Immediately-available Input Method Using One-handed Motion in Arbitrary Postures	D	Hand	Semaphoric	Computer input	Accelerometer	Not specified	Wrist device	y	n		n	4	

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118	C. Amma, M. Georgi and T. Schultz	2014	Airwriting: a wearable handwriting recognition system	D	Hand	Semaphoric	Handwriting recognition	Accelerometer; Gyroscope	HMM (Hidden Markov Models) algorithm	n	y	n		n	9	
119	N. Rossol, I. Cheng, S. Rui and A. Basu	2014	Touchfree medical interfaces	D	Finger; Hand	Semaphoric	Interaction with a display/projection	LEAP motion controller	Library - Leap Motion SDK	Hand held tool (pen, marker, stylus, needle, probe, laser pointer etc.)	y	n		n	12	
120	F. Saxen, O. Rashid, A. Al-Hamadi, S. Adler, A. Kernchen and R. Mecke	2014	Image-Based Methods for Interaction with Head-Worn Worker-Assistance Systems	D	Hand	Semaphoric	Interaction with augmented reality	Camera (RBG, VGA, web)	HMM (Hidden Markov Models) algorithm	HMD	y	n		n	61	
121	Y. Gangman and N. Y. Yen	2014	Development of Highly Interactive Service Platform for Social Learning via Ubiquitous Media	D	Hand	Semaphoric	Interaction with augmented reality	Kinect camera	Not specified	n	y	n		n	Not specified	Questionable quality of information

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
122	M. G. Jacob and J. P. Wachs	2014	Context-based hand gesture recognition for the operating room	D	Hand	Semaphoric	Navigation/Selection in an app	Kinect camera	HMM (Hidden Markov Model) algorithm; Library - OpenNI SDK	n	y	n		n	10+20+19	
123	A. Widmer, R. Schaer, D. Markonis and H. Muller	2014	Gesture interaction for content-based medical image retrieval	D	Finger	Semaphoric	Navigation/Selection in an app	LEAP motion controller	Not specified	Keyboard	y	n		n	2	
124	L. Huang, Z. Zhou and R. Liu	2014	Research on Interaction-oriented Gesture Recognition	D	Hand	Semaphoric	No specific application yet	Accelerometer	HMM (Hidden Markov Models) algorithm	Micro controller	y	n		n	10	Questionable quality of information
125	Y. Zhou, Z. Cheng, L. Jing, J. Wang and T. Huang	2014	Pre-classification based hidden Markov model for quick and accurate gesture recognition using a finger-worn device	D	Hand	Semaphoric	No specific application yet	Ring shaped device (Magic Ring) with a tri-axis accelerometer	HMM (Hidden Markov Models) algorithm	Magic Ring	y	n		n	Not specified	

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126	D.-L. Dinh, J. T. Kim and T.-S. Kim	2014	Hand Gesture Recognition and Interface via a Depth Imaging Sensor for Smart Home Appliances	S	Hand	Semaphoric	Home appliance control	Creative interactive gesture camera	Not specified	n	y	n		n	5	
127	V. Alvarez-Santos, R. Iglesias, X. M. Pardo, C. V. Regueiro and A. Canedo-Rodriguez	2014	Gesture-based interaction with voice feedback for a tour-guide robot	D	Hand	Semaphoric	Robot/avatar interaction	Kinect camera; Range camera and a laser scanner (for human detector)	Original Algorithm; Final State Machine (FSM)	n	y	n		n	12	
128	W. Liu, Y. Fan, Z. Li and Z. Zhang	2015	RGBD Video Based Human Hand Trajectory Tracking and Gesture Recognition System	D	Hand	Semaphoric	Sign Language Input	Kinect camera	Original Algorithm - Salient skin, motion, and depth based particle filter (SSMD-PF)	n	y	n		n	12	
129	T. Kapuscinski, M. Oszust, M. Wysocki	2015	Recognition of Hand Gestures Observed by Depth Cameras	D	Hand	Semaphoric	Sign language input	Kinect camera; ToF (time-of-flight) camera	DTW (dynamic time warping) algorithm	n	y	n		n	Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
	and D. Warchol															
130	P. Trigueiros, F. Ribeiro and L. P. Reis	2015	Generic System for Human-Computer Gesture Interaction: Applications on Sign Language Recognition and Robotic Soccer Refereeing	D	Hand	Semaphoric	Sign Language input; Game control	Kinect camera	HMM (Hidden Markov Models) algorithm; SVM (Support Vector Machine) algorithm	n	y	n		n	Not specified	
131	V. K. Adhikarla, G. Jakus and J. Sodnik	2015	Design and evaluation of freehand gesture interaction for light field display	D	Hand	Semaphoric	Interaction with augmented reality	LEAP motion controller	Not specified	Projection based light field displays	y	n		n	12	
132	R. Alves, A. Negrier, L. Sousa, J. M. F. Rodrigues, P. Felisberto, M. Gomes and P. Bica	2015	Interactive 180° Rear Projection Public Relations	D	Hand	Semaphoric	Robot/avatar interaction	Kinect camera	Kinect SDK	Speech	y	n		n	Not specified	

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133	K. Kim, J. Kim, J. Choi, J. Kim and S. Lee	2015	Depth camera-based 3D hand gesture controls with immersive tactile feedback for natural mid-air gesture interactions	D	Hand	Semaphoric	No specific application yet	Kinect camera	DTW (dynamic time warping) algorithm	Piezoelectric actuator	y	n		n	6	
134	D. G. Santos, B. J. T. Fernandes and B. L. D. Bezerra	2015	HAGR-D: A Novel Approach for Gesture Recognition with Depth Maps	D	Hand	Semaphoric	Game control; Medical Applications; Sign language	Kinect camera	Hybrid approach for gesture recognition with depth maps (HAGR-D) - CIPBR (convex invariant position based on RANSAC) algorithm; DTW (dynamic time warping) algorithm; HMM (Hidden Markov Models) algorithm	n	y	n		n	10	

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135	I.-a. Zaii, S.-g. Pentiuc and R.-d. Vatavu	2015	On free-hand TV control: experimental results on user-elicited gestures with Leap Motion	D	Hand	Semaphoric	Home appliance control	LEAP motion controller	Not specified	n	y	partially	y	n	18	
136	T. Marasovic, V. Papic and J. Marasovic	2015	Motion-Based Gesture Recognition Algorithms for Robot Manipulation	D	Hand	Semaphoric	Robot control	Accelerometer	HMM (Hidden Markov Models) algorithm; DTW (dynamic time warping) algorithm; Distance metric learning	Phone	y	n		n	7	
137	G. Cicirelli, C. Attolico, C. Guaragnella and T. D'Orazio	2015	A Kinect-based Gesture Recognition Approach for a Natural Human Robot Interface	D	Hand	Semaphoric	Robot control	Kinect camera	Original Algorithm; Library - OpenNI	n	y	n	?	n	Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
138	D. Xu, X. Wu, Y.-l. Chen and Y. Xu	2015	Online Dynamic Gesture Recognition for Human Robot Interaction	D	Hand	Semaphoric	Robot control	Kinect camera; RGB-D camera	HMM (Hidden Markov Models) algorithm; Library - OpenCVSharp	n	y	n		n	10	
139	H. Wu, J. Wang and X. Zhang	2016	User-centered gesture development in TV viewing environment	D	Hand	Semaphoric	Home appliance control	Camera (RBG, VGA, web)	Not specified	n	y	n	y	n	24	
140	A. Braun, S. Zander-Walz, M. Majewski and A. Kuijper	2017	Curved-free-form interaction using capacitive proximity sensors	D	Hand	Semaphoric	Interaction with a display/projection	Capacitance sensing	SVM (Support Vector Machine)	HMD	y				10	
141	O'Connor T F, Fach M E, Miller R, Root S E, Mercier P P, Lipomi D J	2017	The Language og Glove: Wireless gesture decoder with low-power and stretchable hybrid electronics	D	Hand	Semaphoric	Sign language input	Glove	Original algorithm	Bluetooth	y				Not specified	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
142	Liu Y, Wang X, Yan K	2018	Hand gesture recognition based on concentric circular scan lines and weighted K-nearest neighbor algorithm	D	Hand	Semaphoric	Not specified	Glove, Camera	KNN, HGR-CCS:		y				Not specified	
143	Memo Ae, Zanuttigh P	2018	Head-mounted gesture controlled interface for human-computer interaction	D	Hand	Semaphoric	Game control, AR interaction	HMD, Depth camera, inertial sensor	SVM (Support Vector Machine)		y				Not specified	
144	Buddhikot, A.G, Kulkarni, N.M, Shaligram, A.D	2018	Hand Gesture Interface based on Skin Detection Technique for Automotive Infotainment System	D	Hand	Semaphoric	Interaction with car controls	RGB camera	Original algorithm	n	y				Not specified	
145	Ma,C, Zhang, Y, Wang, A, Wang, Y, Chen, G	2018	Traffic Command Gesture Recognition for virtual urban scenes based on a spatiotemporal convolution neural network	D	Arm	Semaphoric	Interaction with a display/projection	Kinect	Spatiotemporal convolution Neural Network (ST-CNN).	n	y				10	
146	Wang X, Tarrio P, Bernardos A M, Metola E, Cesar J R	2018	User-independent accelerometer-based gesture recognition for mobile devices	D	Hand	Semaphoric	Robot control	Accelerometer	DTW, original algorithm	Phone	y	n	n	n	14	

#	Author	Year	Title	S (S) or D (D)	Finger/ Hand/ Arm	Classification of gestures	Application	Technology	Recognition method	Supporting technology	Prescribed	Free-form	User defined	Imitation	Number of participants	Quality of information
147	Zeng W, Wang C, Wang Q	2018	Hand gesture recognition using LEAP Motion via deterministic learning	D	Hand	Semaphoric	Data input/authentication	LEAP	RBF neural networks	n	y	n	n	n	10	
148	Huang J, Jaiswal P, Rai R	2018	Gesture-based system for next generation natural and intuitive interfaces	D	Hand	Semaphoric	Data input/authentication, 3D modelling	Soft Kinetic DepthSense (DS325)	SVM (Support Vector Machine)	n	y	n	n	n	Nor specified	

Appendix B – Pilot studies

Appendix B describes the setup of the pilot studies and their findings. Pilot studies were performed to test the study setup and approach, and refine it before the full study had taken place.

B 1 Pilot study 1

Pilot study 1 was a preliminary exploratory study testing the validity of use of 2D screens and the methodology for stage one of the full study i.e. pre-defined activities participants reacted to in a limited time frame. It aimed to establish if the participants perceive 3D objects shown on large 2D screens as 3D objects, and provide an early indication of if there are instances of repetition of the same gestures for the same activities, both between and within the participants. The 3D objects were the individual entities shown to the participants.

Two key parameters to test in the Pilot study 1 were:

- Can a 2D screen be used for the visualisation of the activities in the 3D environment i.e. are activities actually being perceived as 3D?
- If no specific instructions are given to the participants, is there repetition within and between gestures participants perform to complete the activities?

B 1.1 Instructions to participants

The participants were instructed to imagine they were controlling the effect they see with their hands. Other than that, they were not given any further limitations and were asked to perform the hand gestures in order to achieve the effects shown to them on the screen. They were told that any hand gesture they perceive as appropriate and the way they would attempt to achieve the activity is allowed. They were not given instructions in terms of how hands should be used nor were number of hands, fingers or arms used mentioned. They were free to perform any gesture they believed would result in the visualised activity. Thus, study participants were free to create their own gestures, and those gestures were unrestricted in-air hand gestures. The activities chosen for inclusion in the study focus on the conceptual design stage, where dimensions and detail are not fully defined, and manipulation and modification of the objects are frequent. The majority of the activities were manipulative, and a small number were modification based activities. The goal was to identify the intuitive and instinctive response to stimuli. The participants were shown each activity twice first, in order to understand what it is they will be asked to achieve. The activity shown was a 3D animation of a manipulation or modification of an object, created in Solidworks, and exported as an .avi video file. The activity was shown to the participants three times. The first two times they saw an activity they were asked to observe it only, and the activity was shown twice to ensure the participants register it fully. When they saw it for the third time, they were instructed to imagine they were causing it using their hands, and perform gestures they believe would result in the activity they see as it happens. Each activity lasted three seconds. This was done to identify the participants' instinctive reaction rather than allow them to think about what they would do in CAD for example. It was hypothesised that a short time interval to perform a known activity would allow the recording of their natural reactions rather than creation of analogies with the way the same activities would be performed using existing interfaces. User focused studies performed by Wobbrock et al. (2009), Hurtienne et al. (2010), Morris et al. (2014), Piumsomboon et al. (2013), or Khan and Tunçer (2019) did not mention the consideration of time limitations. Eris et al. (2014) and Cash and Maier (2016) observed designers working in a team, an uninterrupted design process, without introducing prompts or time limitations. However, designing in a group would have set a pace naturally. Introduction of explicit time limitation in the study reported on in this thesis emulated the pace that can exist in design work naturally. The simulation of the object manipulation and modification emulates a single designer working on their own, and the focus was on user generated in-air gestures. Participants were not told what the purpose of the study was until after all the activities were complete, to avoid influencing their choices. If they asked about how they should interact in a specific case they were told that however they perceive the situation will be the right way to perceive it, and all reactions are valid.

B 1.2 Setup

The participants[1] were seated at one end of a table, and a large 2D screen the animations were shown on was at the other end of the table, along with a camera positioned under the screen, recording the participants. Their hand motions were also recorded using a LEAP Motion sensor (LEAP MOTION INC., 2017) secured to the table under their arms, as shown in Figure 3.

Figure 3 : Participant taking part in the study – Front camera view

It was found that the range of recording LEAP Motion sensor supported was too small for the requirements of the study, making it an unreliable tool. The hands were fully recorded in only 7 out of 69 gestures. In the remainder they were either not

[1] Ethical approval has been sought and approved via Department of Design Manufacturing Engineering Management at University of Strathclyde. The forms are appended in the Appendix C.

captured or they slowly moved out of the zone covered by the LEAP as the gesture progressed. Participants were not told that there were any limitations to the LEAP range, as the goal was to focus their attention on the activity shown on the screen and discover their intuitive reactions to it. Participants could have been made aware of the range of the LEAP sensor, or allowed to see if the sensor is detecting their gestures or not in one corner of the screen. However, it was deemed that would serve as a distraction and potentially limit their gestures, as they could feel restricted to the LEAP sensor range even if they were not explicitly asked to restrict themselves to it. Therefore, LEAP motion sensor recordings were not included in the analysis of the pilot study, and as LEAP did not provide sufficient quality or range of recording, it was excluded from the full study. The findings presented were based on the video camera recordings only. During the analysis of the pilot study results it was noted that in two cases out of 69 it would have been beneficial to have a side view of the scene, in order to identify the depth of the motion observed. To ensure gestures in the full study were captured from both viewpoints, it was decided to use two cameras, one placed in front of the participant, and one placed to the left of the participant at 90 degrees that could be used to identify the depth of motion if needed. It was suspected that for a smaller degree of motion it could be difficult to establish if the hand moved towards and away from the screen.

B 1.3 Participants

Seven participants took part in the Pilot study 1. They were slightly more experienced than the participants of the full study, but had a similar educational profile which ensured the findings from the pilot study can be considered as a guide. They had a minimum of five and a maximum of ten years of product design experience. All have completed a product design course, or a very closely related undergraduate course including a number of design classes, and were at the time Pilot study was performed design focused PhD students or post-doctoral researchers. Their ages ranged from 24 to 29. Four participants were male and three were female. All were right handed.

B 1.4 Objects and activities

The objects chosen for inclusion on the Pilot study 1 were geometrically simple and had low level of detail. This choice was made in order to minimise the time required for participants to perceive their shape upon viewing. A mix of objects was use, some possessing associated recognisable function some not. Figure 4 shows three 3D objects used in the Pilot study 1: irregular sphere (a), phone (b) and box with a console (c)/hole (d). Irregular sphere and a box with a hole or a console did not have an assigned recognisable function indicated by their shape. While it could be imagined that different participants might have potentially assigned different functions to them e.g. throwing a ball, they did not have a function implied by their shape as a model of the mobile phone did. Different objects were chosen so the impact of the familiarity of the object on the interaction with the object could be observed e.g. would hands take the same form and follow the same path during the interaction with a phone in the virtual environment and the physical world. Types of activities that could be performed using these objects were also a factor considered for the inclusion. The phone and the sphere did not have clearly visible surfaces that could be easily extruded or cut from the objects, so the extrude and cut activities were performed on the box.

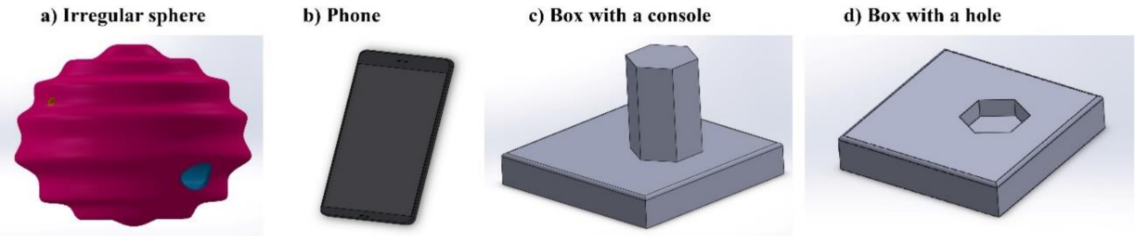

Figure 4 : 3D models used in manipulation and modification activities

Animations of objects being manipulated or modified in the 3D environment were created to visualise the 13 activities shown in Figure 5.

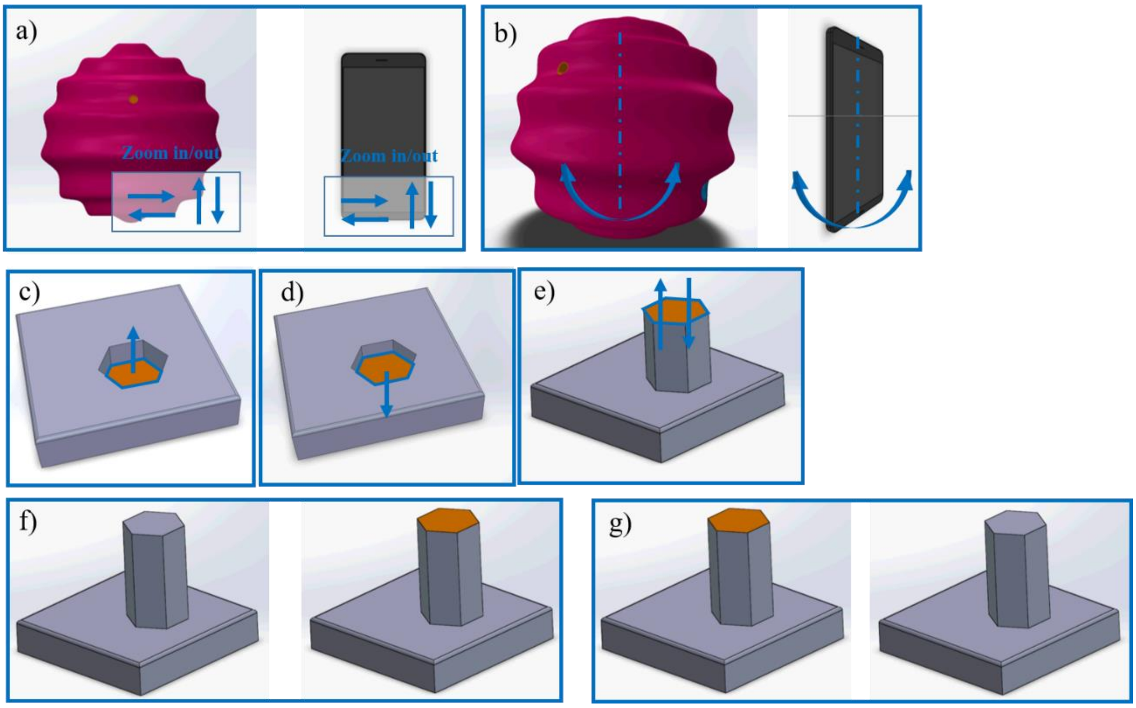

Figure 5 : Activities performed on 3D objects; a) Translate up /down/left/right, Zoom in/out; b) Rotate clockwise/counter clockwise, c) Extrude cut shallower, d) Extrude cut, e) Extrude up/down, f) Select, g) Deselect

The same activities, translate, rotate and zoom, were performed using the sphere and the phone models, and this was done in order to explore if the recognisability of the object affects the interaction with it. Extrude cut activity had two variations, based on the direction of the extrusion. Extrude cut shallower was reducing the volume being extruded, whereas extrusion cut was increasing it. Each participant was asked to perform gestures to complete eleven activities: two rotations (one with each model type), two translate activities (one left or right, and one up or down, one with each model type), two zoom activities (one with each model type), one extrusion, one extrude cut activity, one selection and one deselection. Manipulative activities (translate, rotate, zoom, select and deselect) were chosen as they are required to position a 3D object a designer is working on. They also appeared in ten out of 25 studies focusing on 3D modelling reviewed in Chapter 3, and their inclusion would allow for comparisons with existing work if it was chosen to be performed in the future work. Extrude activities modified the shapes but only along one axis and in one direction in each variant of the activity, aiming to ensure the activity can be perceived and performed within the three seconds allocated to it. The choice of limiting number of different activities to one per participant was made to minimise the overall number of activities per participant, so that the length of duration of each segment of the study could be kept at the minimum and ensure the participants' full attention. It was deemed that even without repetition of each activity by each participant sufficient amount of data to draw preliminary conclusions from would be collected. The goal of the Pilot study 1 was not to identify the frequently repeated gestures and match them to specific activities, instead the intention was to compare the types of gestures performed and establish if repetition of same types of gestures for same types of activities occurred.

B 1.5 Findings

Camera recordings were reviewed and coded by two coders, and gestures were sketched and grouped. The sketches can be seen in Appendix F, Section F 1. The coding guide for Pilot study 1 can be found in Appendix D. Gestures were sketched from the point of view of the front camera recording them, but when described the default orientation adopted was the participant's point of view. Gestures were first classified based on the paths travelled by the participants' hands and grouped by similarity of paths. The shape hand formed while travelling the path was initially not considered, as long as the path was the same. For example for "zoom in" four groups of gestures were identified: pulling the object up, pulling the object back, pulling two fingers apart to stretch the object and pushing the object to the front. In the second step, the gestures were coded to note if hand performing the motion formed a grasping form. A grasping form was considered to indicate the virtual object was being "picked up" or held. Finally, gestures were coded to ascertain if the participants were interacting with virtual objects as they would with a physical 3D object suspended in the air in front of them (Vuletic et al., 2018). At this stage, whether gestures were classified as 2D or 3D interaction was determined based on if 3D motions of the object displayed on screen were mimicked, or if the participants were performing gestures that indicated interaction with a 2D screen e.g. pinching or touching the imaginary virtual plane. It would be assumed that the interaction was with a 2D screen if gestures were performed in a vertical plane only, even if objects on the screen were moving three-dimensionally. In the full experiment this definition was extended, based on the discussions held between two coders during Pilot study 1 coding, to ensure the coders have a clear unambiguous guide to follow, and is reported in Chapter 5 Section 5.2.4.

Two parameters to be tested (SectionB 1) were decomposed into four hypotheses:

1. *There is repetition between subjects for the same activities* – Are different participants performing the same gestures for the same activity, independently and without guidance or limitations? For example, did different participants use the same gesture to zoom in when interacting with an object?

2. *There is repetition within subjects for the same type of gestures* - Does a designer use the same gesture to perform the same type of an activity? For example, the same gesture is used by the same designer to rotate two different objects at two different temporal instances.

3. *3D representation shown on a 2D screen does not significantly affect the perception of the 3D object* - Participants interact with a 3D object shown on a 2D screen as if it was a physical object suspended in the air in front of them.

4. *Type of the 3D object being manipulated (recognisability of its function) affects the gesture* - Designers grasp 3D models of objects with recognisable functions, but not those of models with non-recognisable functions. For example, 3D model of a phone is grasped, but a spherical object is not.

For small samples, analysis can show statistically significant results that are still subject to high margins of uncertainty (Button et al., 2013, Hay et al., 2017). The number of samples for gesture per each activity (Hypothesis 1 and 2) at five gesture pairs per participant was too small to justify the statistical analysis at the pilot stage. For the 2D/3D coding (Hypothesis 3), and recognisability measure (Hypothesis 4) only one parameter is observed across the entire sample, making the sample 10 per participant (double the size) and statistical analysis was applied. For hypotheses three and four inter-coder reliability was calculated using Krippendorff's Alpha reliability estimate, as these hypothesis required coding that required interpretation of gestures.

Krippendorf's alpha measure of reliability is considered to be a suitable measure due to its generality and ability to be used regardless of "the number of observers, levels of measurement, sample sizes, and presence or absence of missing data"(Hayes and Krippendorff, 2007). It results in a statistical measure of agreement among coders of data and indicates their reliability. Agreement of $\alpha \geq 0.8$ is customarily required, with values of $\alpha \geq 0.667$ the lowest required value where tentative conclusions are acceptable (Krippendorff, 2004). Two coders were involved, the author of the thesis (Coder number 1) and Coder number 2. For hypothesis one and two no interpretation was involved as activities performed were literally described. For hypothesis three the coders agreed in 100% of the cases, and alpha value was 1. For hypothesis four they agreed in 83% of the cases, and the alpha value was 0.65. This alpha value is not high enough to assume sufficient level of agreement, and cases where the coders disagreed were examined in order to identify the cause of disagreement. This led to change to the coding guide and the requirement to determine the recognisability of objects. Instead, the gestures performed were classified and compared. If the same gesture was performed for different objects then it was concluded that recognisability of the function of the object does not influence the gestures. More detail is provided in the main body of the thesis, Section 7.2.

B 1.5.1 Hypothesis 1 - Findings on gestures per activity

Observing gestures performed by different participants for the same activities, it was concluded that while a number of different gestures were proposed for 13 different activities, if they are summed up 81% of them were repeated by at least two and up to 6 out of 7 participants, as can be seen in Table 2. The same combination of hands was not always used e.g. some participants used left hand to hold an object and right hand to modify it, while others used their right hand to hold an object and their left hand to modify it. However at this stage, both due to only including six participants and early stage of research handedness was not considered. It would only become significant during implementation and assignment of a left or right hand as dominant. Use of their left or right hand was indicated in the brackets - L indicates use of left hand, R use of right hand, B use of both hands (where both hands were used performing the same or mirrored movement), RD use of both hands where right hand used for the dominant movement, and LD use of both hands used where left hand used for the dominant movement. For the selection and deselection of a surface similar gestures were used, but the selection/deselection itself was inferred either using a flicking motion (denoted by F in the superscript), index finger or the entire hand waving the surface away, or tapping motion (denoted by T in the superscript), index finger or the entire hand touching the surface briefly. The number of fingers used was not taken into account at this stage, as long as the paths travelled by hands were the same the gestures are categorised as same. The distances travelled by the hands were not measured, and paths were considered to be the same as long as the coders agreed that the intent of the motion was the same e.g. if the vertical downward motion performed to translate down diverged from the perfect vertical path by less than approximately 10 degrees it was still considered to be a downward motion following a vertical line. Larger divergences did not occur in this sample.

Table 2 : Gestures performed by different participants for the same activities (arranged as manipulative first in alphabetical order, selection/deselection gestures, and then gestures modifying the shapes)

Gesture	Different participants performed the same gesture for the same activity		Number of gestures that were not repeated	Total
	1st type of gesture	2nd type of gesture		
Rotate cw	4 (1L+1R+2B)	0	3	7
Rotate ccw	3 (2R+1B)	3 (2BLD+1BRD)	1	7
Translate down	5 (2R + 3B)	0	1	6
Translate up	0	0	2	2
Translate left	2 (2B)	0		3
Translate right	3 (1L+2R)	0		3
Zoom in	4 (2R+2B)		3	7
Zoom out	6 (4R+2B)		1	7
Deselect surface	5 (1^T BLD +1^F BLD + 1^T BRD +2^F BRD)	2 (2R)		7
Select surface	5 (2BLD+ 2^TBRD +1^F BRD)	2 (2R)		7
Extrude cut	3 (1BLD + 2 BRD)	0		3
Extrude cut shallower	3 (3BRD)	0	1	4
Extrude up	5 (2BLD + 3BRD)	0	1	6

Some examples of activities most frequently performed using repeating one (a) or two gestures (b and c) are shown in Figure 6. *Translate down* was performed the same way by five participants, and only one additional participant performed a different gesture for *translate down* activity shown in Figure 6 a. *Selection* activity was performed by five participants using the gesture shown in Figure 6 b, and two times using the gesture shown in Figure 6 c.

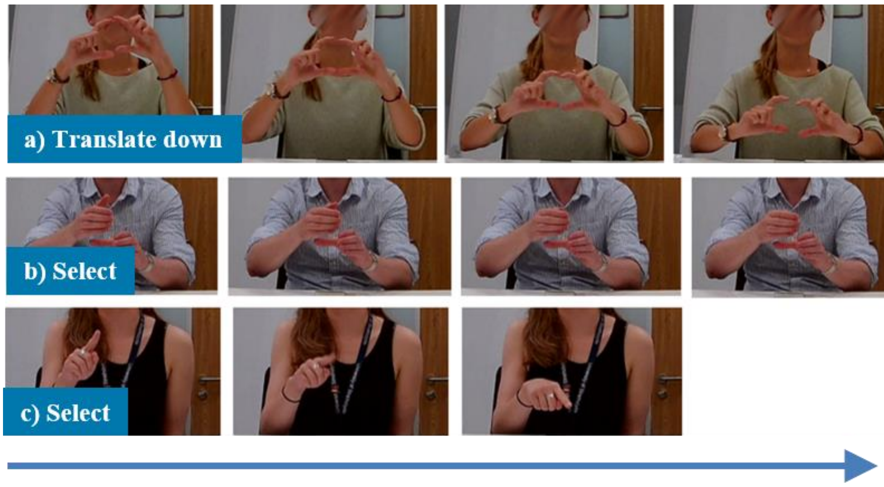

Figure 6 : Examples of repeated gestures for *translate down* activity (a), and *select* activity (b and c)

There were exceptions where two different gestures were performed by two different participants to *translate up*, and there was no repetition. The participants were asked to perform only two *translation* activities in total and the variant of *translation* activity given to each of them (up/down/left/right) was random. Hence totals for translation activities differ, and a larger number of repetitions, ten at the minimum, per specific variant of translate gesture would be required to reach reliable conclusions. This is why it was decided that in the full experiment all participants will perform all the activities. Similarly, the totals on the extrude type gestures (*extrude cut*, *extrude cut shallower* and *extrude up*) vary, as each participant was only asked to perform one extrude type gesture. One participant failed to complete the *extrude up* gesture, resulting in only six *extrude up* gestures in total.

B 1.5.2 Hypothesis 2 - Findings on repeated gestures per participant

It was found that the majority of participants consistently used the same gestures for the same activities applied to different 3D objects, as shown in Table 3. This was the case in 71% of *zoom*, *translate* and *rotate* activities where participants used the same type of a gesture (classified by the path travelled by hands, as defined in Section B 1.5.1). Again, they did employ different hands or different number of fingers to manipulate objects in 40% of those for *translate* activities and 60% for *zoom* and *rotate* activities. *Extrude cut* and *extrude up* were all performed using the same type of a gesture. *Selection* and *deselection* were performed using the same arrangement of hands by 57% of participants, and 43% used a partial version of the gesture (dominant hand was used for selection, but the object was not held with the other hand). If both hands were used 80% of participants used the flicking gesture to *select/deselect*. When only one hand was used all participants used the tapping gesture.

Table 3 : Number of repeated gestures for the same type of activity by the same participant (arranged as manipulative first in alphabetical order, selection/deselection gestures, and then gestures modifying the shapes)

Gesture	Same gesture same hand use	Same gesture different combination of hands used	Different gestures	Total
Rotation	3	2	2	7
Translation	2	3	2	7
Zooming	2	3	2	7
Select/deselect	1^T+2^F	1^F	3^T	7
Extrusion	6			6

B 1.5.3 Hypothesis 3 - Interaction with 3D objects shown on a 2D screen

Considering how ubiquitous 2D screens are in daily use, e.g. phones, tablets, touchscreens, it was expected some of the interaction paradigms would appear in the interaction with 3D objects shown on 2D screens. Morris et al. (2014) call this legacy bias. However, it was found that over 80% of the gestures each participant performed showed interaction with the virtual object appears to have been performed as if the user interacted with a physical object suspended in the air in front of them. Even more than that, 94%, have been performed out of the bounds of a vertical 2D plane the objects were shown in. For example, most *rotations* were performed by participants holding the axis of rotation of an object in place with one hand, and using the other hand to rotate the object around it tracing a circle in a plane perpendicular to the “held” axis, as shown in Figure 7a. *Zooming* is another example. In interaction with 2D surfaces to *zoom in* or out typically tips of two fingers are moved closer together, or further apart, in one plane, following a straight line. Instead, the majority of participants pulled back or pushed forward the imaginary 3D object to *zoom in* or *out*, as shown in Figure 7b.

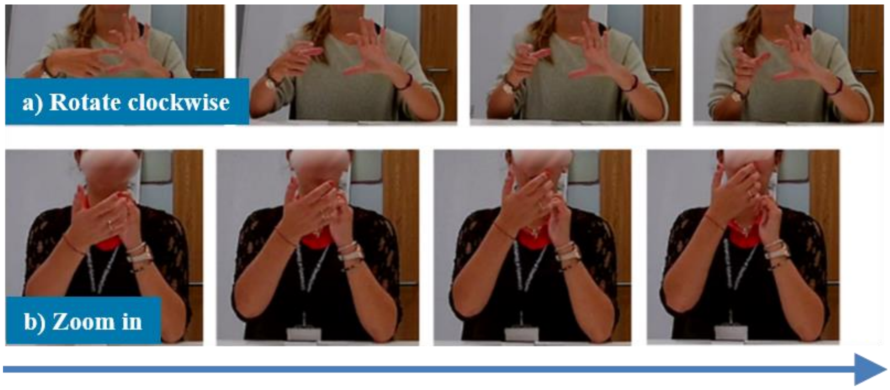

Figure 7 : Examples of three-dimensional interaction

Chi-square goodness of fit was used to test if this could have happened by chance (Vuletic et al., 2018). The null hypothesis for this test was that roughly the same number of gestures would be interacted with as if they were perceived as 2D objects on a screen or 3D objects suspended in air in front of the participants (H0), and observed and expected number of counts for 2D and 3D interactions is given in Table 4.

Table 4 : Observed counts of 2D and 3D interactions with a virtual model

Type of interaction	Observed counts of 2D/3D	Expected counts of 2D/3D
2D	3	34.5
3D	66	34.5
Grand total	69	69

The formula used for calculation of Chi square value is:

$$X^2 = \sum \frac{(O-E)^2}{E} = \frac{(66-34.5)^2}{34.5} + \frac{(3-34.5)^2}{34.5} = 57.522;$$

Where O – observed frequency, E – expected frequency.

ν = (number of categories after pooling) – (number of parameters estimated) – 1=1

v stands for degree of freedom, and it determines which table the values for p are read from based on the X^2 value. Tables are built into the SPSS which was used for the calculation. If the p value is <0.05 (5% of the sample) then the observed activity is considered to be significantly different than what would be expected to happen by chance.

The obtained Chi-Square value (57.522) has a p of 0.000: this is < 0.05, and the conclusion is that the observed frequencies of use of 3D based interaction are significantly different from what would be expected to happen by chance. This indicates that participants perceive objects as 3D, even when they see them on a 2D screen. However, as the Pilot study 1 did not include a post experiment questionnaire, it is impossible to claim what their perception was with certainty. Following this conclusion, the decision was made to include a post study questionnaire in the full study including this question explicitly to be able to evaluate the assumption. However, as the gestures performed tended to use the three-dimensional space rather than single plane the object was shown in, possibly indicating 3D perception, the decision was also made to retain the use of inexpensive 2D screens for the initial gesture elicitation and cameras for gesture recording. If the full study questionnaire shows that the assumption was wrong a second study would be designed using a VR environment.

B 1.5.4 Hypothesis 4 - Effect of 3D object recognisability on the nature of interaction

Out of the three objects used in the Pilot study 1 (irregular sphere, a mobile phone, and a square box), the mobile phone was the only object assumed to carry familiar function with it i.e. participants would have the experience of handling it habitually in the physical world. The use of a grasping gesture was defined as an indicator of recognisability of a function an object of a particular shape has, as to turn, push away or otherwise interact with a mobile phone physically, users would first need to grasp it to secure a hold of it (Vuletic et al., 2018). The null hypothesis of the study was that there would be no significant association between the shape of the object and type of the interaction with it (grasping in this case). As in Section B 1.5.3, Chi-square test of association between two independent variables was used, and observed number of gestures, both grasped and not, are shown in Table 5.

Table 5 : Summary of number of gestures which included or did not include grasping (Vuletic et al., 2018)

Observer	Grasp	Sphere	Phone	Box	Total
1	**Y**	12	13	13	39
1	**N**	9	14	8	30
2	**Y**	10	19	13	42
2	**N**	11	8	8	27

A 2x2 table had (3-1) x (2-1) = 2 degrees of freedom.

$$Xcoder1^2 = \sum\frac{(O-E)^2}{E}\frac{\left(O_{1,1}-E_{1,1}\right)^2}{E_{1,1}} + \frac{\left(O_{1,2}-E_{1,2}\right)^2}{E_{1,2}} + \frac{\left(O_{1,3}-E_{1,3}\right)^2}{E_{1,3}} + \frac{\left(O_{2,1}-E_{2,1}\right)^2}{E_{2,1}} + \frac{\left(O_{2,2}-E_{2,2}\right)^2}{E_{2,2}} + \frac{\left(O_{2,3}-E_{2,3}\right)^2}{E_{2,3}}=0.956;$$

$$Where\ E_{1,1} = \frac{39\times(12+9)}{69},\ O_{1,1} = 12,\ \ ,E_{1,2} = \frac{39\times(13+14)}{69}, O_{1.2} = 13,\ E_{1,3} = \frac{39\times(13+8)}{69}, O_{1.3} = 13,\ E_{2,1} = \frac{30\times(12+9)}{69}, O_{2,1} = 9,\ E_{2,2} = \frac{30\times(13+14)}{69}, O_{2.2} = 14, E_{3,2} = \frac{30\times(13+8)}{69}, O_{3.2} = 8$$

$$Xcoder2^2 = \sum\frac{(O-E)^2}{E}\frac{(66-34.5)^2}{34.5} + \frac{(3-34.5)^2}{34.5}=2.581;$$

$$Where\ E_{1,1} = \frac{42\times(10+11)}{69},\ O_{1,1} = 10,\ \ ,E_{1,2} = \frac{42\times(19+8)}{69}, O_{1.2} = 19,\ E_{1,3} = \frac{42\times(13+8)}{69}, O_{1.3} = 13,\ E_{2,1} = \frac{27\times(10+11)}{69}, O_{2,1} = 11,\ E_{2,2} = \frac{27\times(19+8)}{69}, O_{2.2} = 8, E_{3,2} = \frac{27\times(13+8)}{69}, O_{3.2} = 8$$

For coder 1 Chi-Square was 0.956, with two degrees of freedom, had a p of 0.620. For coder 2 Chi-Square was 2.581, with two degrees of freedom, had a p of 0.257. Both meant the null hypothesis cannot be rejected, and there was no proof of significant association between shape and grasping.

However, the discussions between the two coders have identified an issue with the use of grasping as an indicator of familiarity with an object. The first coder required the shape of the hand to be in a form of a grasp, and believed that would indicate the user was picking up a physical object. The second coder assumed a grasp even in cases where the hand shape was not in the form of a grasp, but it was clear that a participant was holding a part of the object down with an open hand. For example, the base of the box console was extruded from was often held down with one open palm, while the other hand was used to extrude the console. How tightly the hand grasped the object was another source of disagreement, and what intensity of grasp would be enough to lift the object. The second coder also believed gravity could be assumed by the participants. To avoid subjectivity in interpretation of recognisability of the objects' function, it was decided that in the full study another object with a recognisable function should be included (a chair). Then instead of interpreting the gesture itself, it could be observed whether the same gesture was used by the same participant during the same activity for all of the objects. Participants would also be advised that the objects do not have a weight assigned, but are virtual visualisations only.

B 1.6 Outcomes of Pilot study 1 and changes propagated to the full study

Outcomes of the Pilot study 1 have confirmed that key parameters were met:

- 2D screen can be used for the visualisation of the 3D activities without significantly influencing the findings i.e. are likely to be perceived as 3D when viewed?
- If no specific instructions are given to the participants, there is repetition both within and between gestures participants perform to complete the activities.

A number of changes were propagated from the Pilot study 1 to the full study, in order to ensure a comprehensive data collection:

- LEAP did not provide sufficient quality or range of recording, and consequently it was excluded from the full study.
- To ensure gestures in the full study are fully covered and depth of the motion can be estimated if required, it was decided to use two cameras, one placed in front of the participant, and one placed at 90 degrees to the left of the participant.
- In the full study it will not be assumed that the participants would perform the translate activity in the same manner regardless of the direction of the

translation, or that variants of the extrude activities would be similar. All participants will perform all of the predefined activities.

- Post study questionnaire would be included in the full study, including explicit questions about participants perceptions of e.g. three dimensionality of the shapes they were interacting with, interaction with objects that poses recognisable assigned function in physical environments.
- To avoid subjectivity in interpretation of object recognisability, an additional object with a recognisable function will be included in the full study (a chair). If the same gesture is used by the same participant for the same activity with the three different objects will be explored rather than interpreting the gesture itself.
- Participants will be advised that the objects do not have a weight assigned, but are virtual visualisations only.

B 2 Pilot study 2

The Pilot study 2 was performed to observe the flow between the gestures, and the sequence of gestures in an uninterrupted design process. Pilot study 1 required participants to react to isolated single activities. Pilot study 2 was designed to observe the flow of activities. It had two stages. The first stage was partially guided and in it the participants were asked to create an object by reaching a number of predefined steps defining different levels of completion of an object, progressively more defined in each step (details of specific steps and objects are given in Section B 2.4). The first stage was also referred to as a guided stage. The second stage only provided an image of the final object to the participants, and they were asked to create it, but they were free to do it in any way they wished to. The second stage was thus also referred to as a free stage, and would allow the collection of information about the preferred sequence of activities during the design process. Inclusion of the first stage ensured that gestures for the predefined steps are recorded, even if some participants fail to fully complete the second stage. Comparing the activities performed in both stages for the same objects would allow for the identification of potential preferred sequence of activities, which could be identified from the second stage.

The goal of this pilot study was to determine:

- If information on the flow between the gestures can be collected, in order to explore how the participants differentiate between different gestures.
- If there is a difference between the number of activities performed in a design sequence with and without guidance., as that would determine if intermediate steps are required in the full study in order to collect information about the gestures performed during an uninteruppted design activity.

B 2.1 Instructions to participants

Instructions for the use of their hands were the same as in Pilot study 1 (detailed in Section B 1.1). In Pilot study 2 participants were additionally asked to imagine they are creating a virtual object in the space in front of them, but were not given any further instructions.

B 2.2 Setup

The Pilot study 2 was performed using the same set up described in Section B 1.2, with the exclusion of the LEAP sensor, due to its limitations.

B 2.3 Participants

Five participants took part in Pilot study 2. Four participants were the same as in the Pilot study 1, and the fifth participant was a new participant with a similar background. Three participants were male and two were female. All were right handed.

B 2.4 Objects and activities

In stage one participants were first asked to create one of the shapes shown to them (these can be seen in Figure 8), and narrate what they were doing.

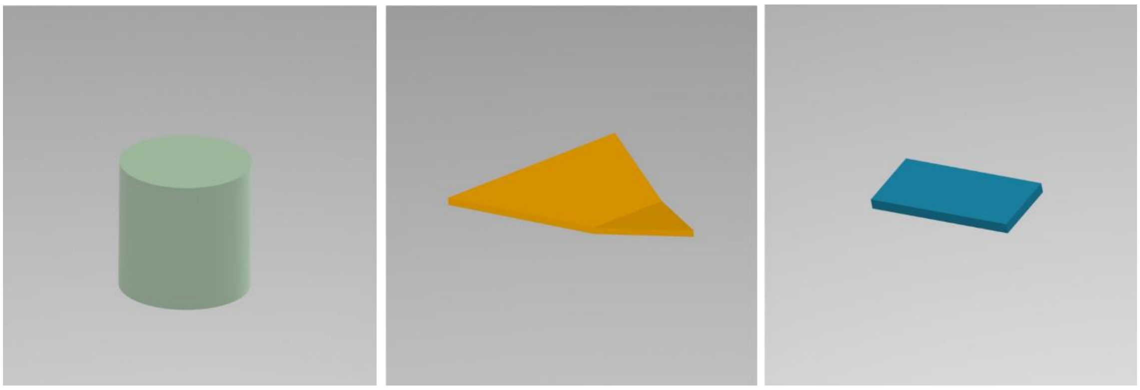

Figure 8 : Pilot study 2, stage one, first step for three different parts

Beyond this point stage one was partially, guided, as once the first shape was "created", participants were shown an additional image where this shape was slightly modified, and asked to now modify the created shape so it matched the appearance of the new shape. They were told they were free to rotate, enlarge or manipulate the shape in any way they felt was needed to perform the activity. The final parts were a cup, a hexagonal plate and a phone cover. This sequencing of predefined steps was performed in order to ensure the participants performed all the key activities of a part design that would typically be performed if part was created using solid modelling in a CAD system e.g. extrusion, shelling, addition of shapes. The steps can be seen in Figure 9. The cup creation sequence had four steps in total, the hexagonal plate creation sequence had two steps, and the phone cover creation sequence had five steps.

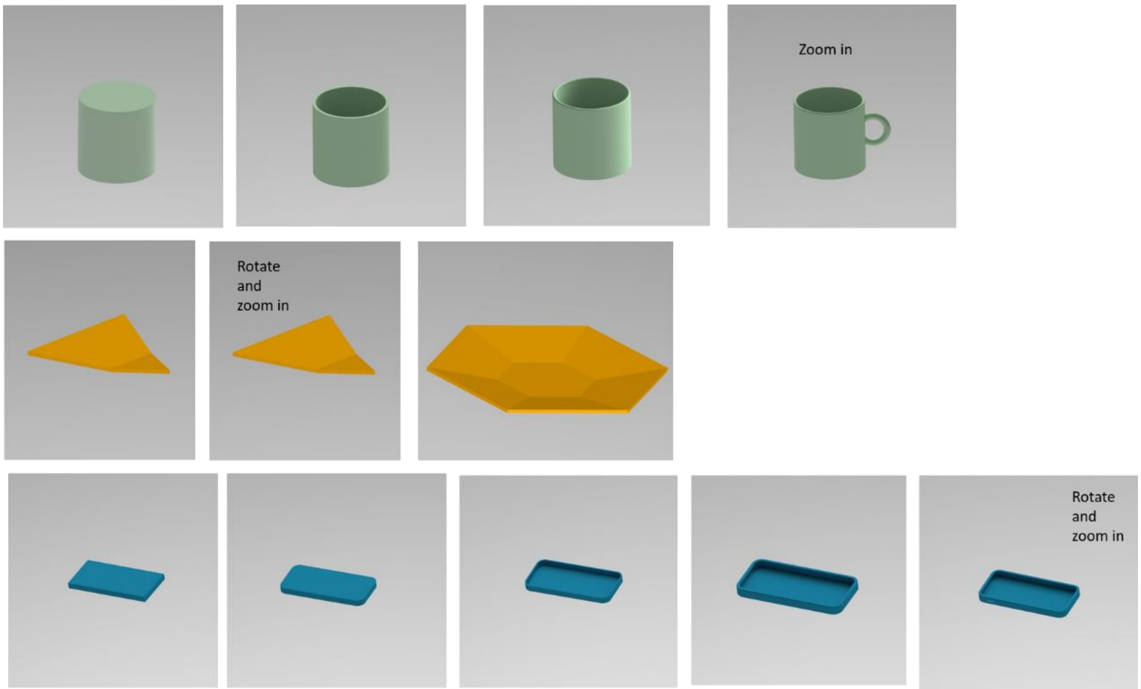

Figure 9 : Pilot study 2, all steps for stage one for all three parts

In stage two, participants were shown an image of a final product, shown in Figure 10. The products were the same three products used in stage one, but for each participant the products used in the two stages were different.

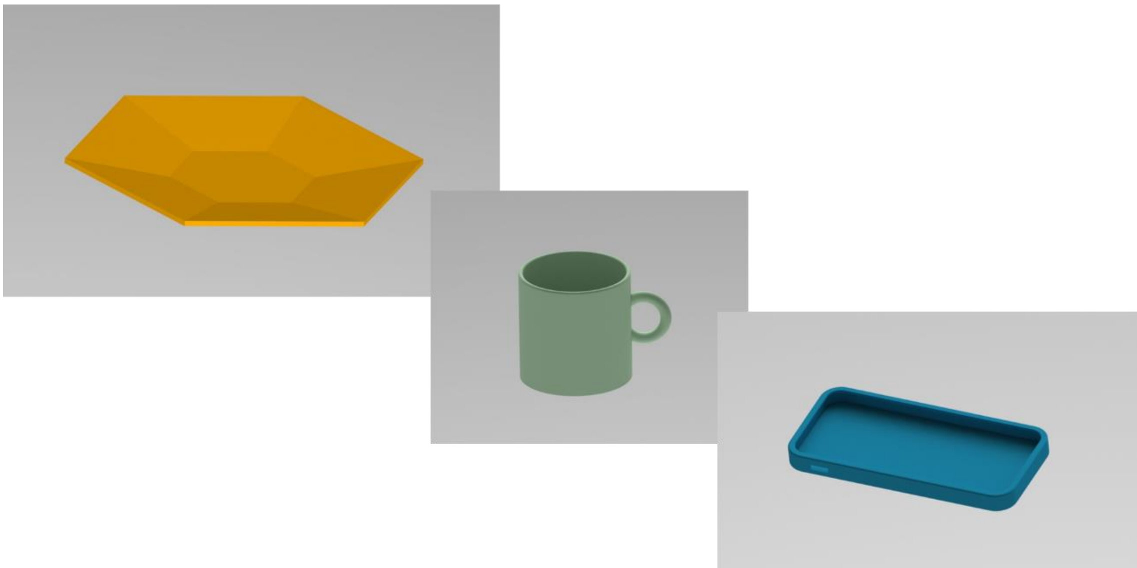

Figure 10 : Final products used in Stage 2 of the Pilot study 2

Combinations of objects for the two stages for different participants can be seen in Table 6.

Table 6 : Presentations containing combinations of objects shown to participants in two stages

Presentation	Stage 1	Stage 2
1	Cup	Hexagonal plate
2	Hexagonal plate	Cup
3	Phone	Cup
4	Cup	Phone
5	Hexagonal plate	Phone

The number of repetitions of specific objects was not considered at this stage, as the goal of the Pilot study 2 was to test the approach rather than provide a detailed analysis of gesture performed in each stage and draw conclusions from it. Hence different objects appear different number of times, cumulatively e.g. cup is present in four presentations, while the hexagonal plate and the cup appear in three. Again, the participants were asked to create the object, following their preferred sequence containing any activities they found intuitive and natural using their hands, while they narrated their activities and thoughts.

B 2.5 Findings

Participants did not report any issues with any of the activities, and all managed to complete both stages of Pilot study 2. They appeared to respond well to the instructions to imagine they were interacting with a virtual shape suspended in the space in front of them. The anonymised screenshots of the process are available in Appendix F, Section F 2.

B 2.5.1 Transitions between gestures

The first goal was to observe the flow between the gestures. Only three different poses were observed between the gestures:

- Hands rested on the table while the participants were thinking about the next step (52 instances).
- Hands remained in the last position they were in at the end of the previous gesture (61 instances).

- Open palms held vertically in the air (two instances, and only Participant 1 had performed this gesture).

It should be noted that for the partially guided stage there were transitions between images shown to the participants, and during these they typically rested their hands on the table, as their flow was interrupted. In the full study, these instances will be excluded from the sample.

B 2.5.2 Sequence of activities for guided and free stages

The guided stage was performed in order to record gestures that are not only manipulative, and partial guidance was given to ensure the participants are able to perform the majority of gestures e.g. so that they do not omit steps. They did have the freedom to choose the activities and gestures performing them within each step of the sequence. All participants performed partially guided stage without any issues.

With the free stage, the concern was that the participants may forget to perform some of the steps, as there would be no guidance or reminders of what they have performed so far. This has materialised in two instances, one instance of hexagonal plate creation, and one instance of phone creation. In these cases the participants only performed the key gestures and disregarded connecting gestures or gestures performing some more detailed activities. The activities and gestures they did perform would not result in the complete object, or some detail would be missing. While this was a drawback of the free stage, it was also noticeable that for the hexagonal plate and the phone cover the sequence of activities and gestures in the free stage tended to be different from the partially guided stage. Creation of the cup followed largely the same sequence of activities in both stages, as shown in Figure 11. Participants created the cylinder, then cut the smaller cylinder out of it, filleted the top edge and created the handle by lofting a small circle around the drawn shape representing the handle centre line. Tables classifying steps and frequency of their performance were shown for guided stages in the left half of the figure and for free stages in the right half of the figure. Number of instances a specific workflow had appeared in is indicated above each workflow, and a short descriptor of each sequence is given in the orange box at the top of each collection of steps. Blue filled in boxes indicated a step was performed by a participant. Step titles that have been repeated by each participant that performed a specific workflow are bolded.

Figure 11 : Creation of a cup - guided and free stages

For the hexagonal plate, all four participants followed different sequences, as shown in Figure 12. In the partially guided stage, the creation of the triangle was identical - draw a triangle then extrude it, but the step where the participants were asked to pattern it around to form a hexagon differed. One participant had set the axis and used a rotational motion to pattern the triangle around it. Another participant multiplied the triangle by pantomiming they were placing additional shapes in required spaces. In the free stage one participant created the shape by creating two hexagonal profiles of different sizes in parallel planes, drawing one edge and then patterning it around the central axis to create the remaining edges. Then the shape was “filled in” and extruded. Other participants drew a hexagon, without assigning it any thickness, and then pulled the middle out to achieve the required shape. Then they defined the bend lines (edges).

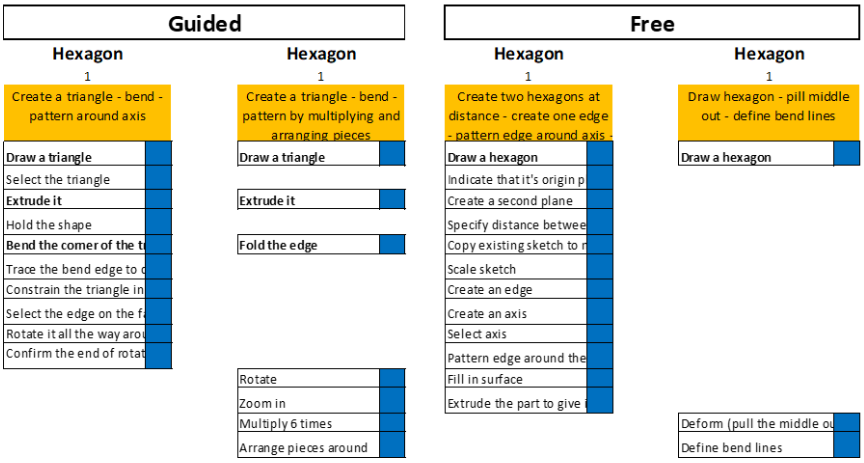

Figure 12 : Creation of a hexagonal plate - guided and free stages

The phone cover creation had two variations, if small differences such as shelling instead of extrusion are disregarded. All four variants are shown in Figure 13, but the first three can be grouped together, as the steps performed followed the typical solid modelling sequence, with small variations. The sequence of activities for the first variation was creation of rectangle, extruding it, fileting the edges, drawing another rectangle and performing extrude cut action or simply shelling the existing rectangle. Finally, a small rectangle is drawn on one of the edges and cut out. Both partially-guided and one of the free stage sequences were performed this way. The first partially guided sequence skips the explicit extrude cut activity for rectangle shelling, but the following steps indicate interaction with the shelled shape, hence it was assumed the step was skipped in error. The second phone cover creation variant is one of the sequences where some steps were skipped in the free stage. A rectangular solid was created that was ”extruded down to shell” without defining what is being extruded. Then the hole for the microphone was cut out on the side edge, but it was not well defined.

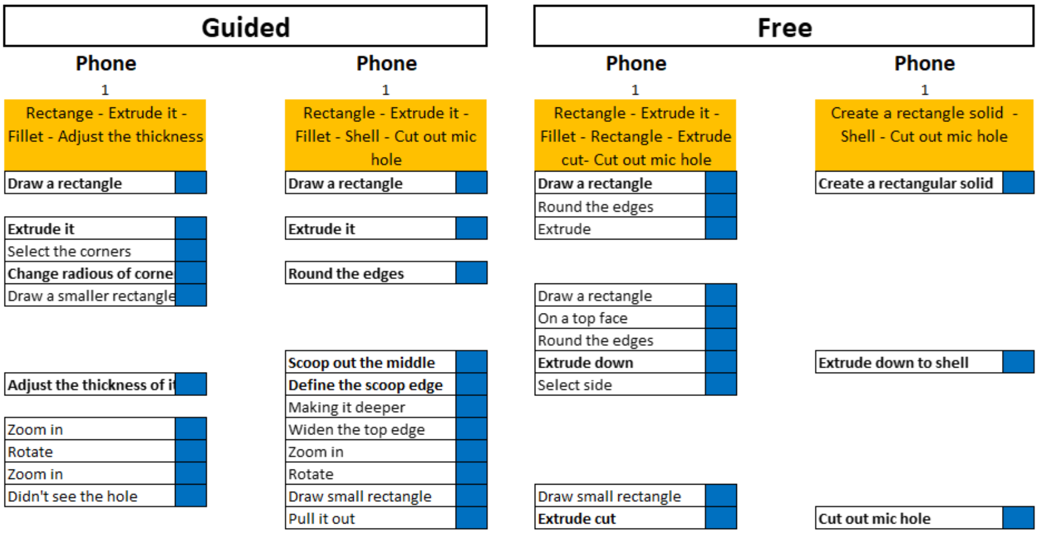

Figure 13 : Creation of a phone cover - guided and free stages

Since the majority of the activities were performed as desired, the approach with a partially guided and free stages was retained for the full study. However for the hexagonal plate and the cup an additional variant was added for each where the last step in the sequence required participants to create a cube and a sphere, respectively. For the hexagonal plate the cube is attached to the bottom of the plate, and for the cup the handle is in the shape of a sphere instead of a traditional hollow handle. This decision was made in order to explore how the participants would create geometrically defined solid shapes, while the sequence of activities for the shape creation remains relatively unchanged.

B 2.5.3 Comparison of gestures performed in Pilot study 1 and Pilot study 2

Pilot study 1 and Pilot study 2 only shared the *zoom* and *rotate* manipulative activities. Additionally, Pilot study 2 focused on testing the approach for identifying the sequence of gestures in an uninterrupted design process rather than gestures themselves. However observing the time participants took to perform the gestures in the Pilot study 2, where they were not time limited, it is noticeable that the duration of gestures is comparable to the 3 seconds the gestures were limited to in Pilot study 1. This further confirmed the time limitation in Pilot study 1 will be retained for the full study. Outcomes of Pilot Study 2, and changes propagated to the full study

Outcomes of the Pilot Study 2 confirmed that key parameters were met:

- Information on the flow between the gestures can be collected.
- Participants can perform a design sequence without being given guidance about intermediate steps. However, since in two cases some steps were ommited the stage one including the intermediate steps providing guidance was retained.

Only one change is propagated form the Pilot study 2 to the full study:

- Variants of hexagonal plate and the cup are added to the objects, in order to retain the objects close to the original shapes and possibly resulting in similar sequences of activities, but allowing collection of data on how solid standard shapes are created.

Appendix C – Ethics approval

Ethics approval for the pilot (Section C 1.1) and full study (Section C 1.2) are given in this appendix.

C 1.1 Ethics approval for the pilot studies

Ethics Committee -
Code of Practice on Investigations on Human Beings

When implementing a staff or student project which involves 'investigation on human beings' it is important to note that the university has a code of practice governing the implementation and conduct of such investigations. This 'code of practice was developed by the 'Ethics Advisory Committee' and approved by the university court on 5th May 2000. The code governs all investigations on human beings including class teaching experiments and demonstrations, student projects and research investigations which fall within the scope of the code. The 'Departmental Research Committee' will act as the 'Departmental Ethics Committee', and can approve most routine, non-invasive investigations.

It is the responsibility of the supervisor to make the student aware of relevant guidelines and ensure that they are observed. The supervisor is also responsible for submitting details of proposed investigations for approval where necessary.

The following contains 2 checklists to aid the implementation of this practice:

(i) The first is to identify cases which require to be approved by the University Ethics Advisory Committee. If any of the boxes are marked in checklist (i) the investigation must be submitted to the university committee for approval.

(ii) The second is to ensure correct procedure is adhered to in any 'routine or non-invasive' investigation i.e. those which are readily approved by the 'Department Ethics Committee' (in essence the checklist represents a summary of Section 6 of the Code of Practice on Investigations on Human Beings.)

These checklists should not be viewed as a substitute for the original document and thus all supervisors should be familiar with the code before utilising these in staff/student research projects. The checklists are designed to ensure that the staff/students are immediately aware of the implications of the guidelines to their investigation. Furthermore, they act as departmental records of staff/student conduct in investigations on humans.

As 'Ethics Advisory Committee' approval of a protocol can take up to 4 weeks (longer for very specific requests), where research is likely to include an element of 'investigations on humans', an analysis of expected procedures should be carried out at as early a stage as possible.

In addition to the university regulations, investigations of a Physiological, Sociological and Biological nature must conform to additional 'codes of practice' set out by relevant professional bodies - in such cases the secretary of the ethics advisory board can supply copies of these statements.

(i) Supervisor and Student Ethics Checklist

Project Title: Gestures for CAD interface – Pilot Study

Participants (staff/students carrying out investigation): PhD Student/Research Assistant Tijana Vuletic will carry out in the investigation. Participants will be PhD students from the department of Design, Manufacture and Engineering Management, University of Strathclyde

Investigation Content: Participants will be asked to observe an object being manipulated on a screen, and then asked to perform gestures which would lead to the same result. Participants will be recorded visually (using one camera) and their hand gestures will be captured using a LEAP sensor placed on the table in front of them. Each individual session will take approximately 15 minutes. Participants will not be remunerated for their time.

Does the investigation involve any of the following (mark as appropriate):

1)	Harm, discomfort, physical or psychological risk (esp. pregnant women, elderly, the young).	yes☐	no☒
2)	Participants whose ability to give voluntary consent is limited (cognitively impaired, prisoners, persons with chronic physical or mental conditions).	yes☐	no☒
3)	Invasive techniques (DNA testing, collection of body fluids/tissue).	yes☐	no☒
4)	Extensive degree or duration of exercise or physical exertion.	yes☐	no☒
5)	Manipulation of human responses (cognitive or affective) which may involve stress or anxiety.	yes☐	no☒
6)	Administration of drugs, liquid/food additives.	yes☐	no☒
7)	Deception of the participants which might cause distress or effect their willingness to participate in the research.	yes☐	no☒
8)	The collection of highly personal, intimate, private or confidential information.	yes☐	no☒
9)	Payment to the participants (other than travel/time costs).	yes☐	no☒

If the answer to <u>any</u> of the above questions is yes you <u>must</u> submit a protocol to the 'Ethics Advisory Committee' unless previous consent has been granted for practising the 'generic' procedure involved. The protocol for such submissions to the 'Ethics Advisory Committee' can be found in Appendix A of the 'Code of Practice on Investigations of Humans Beings'.

Supervisors Signature(s)

.... Date 9/8/17.......

.... Date ....

Students/Researchers Signature(s)

.... Date 09/08/17

.... Date ....

(ii) Checklist for Department Approved Investigations

Mark all boxes when you have read, understand and, where appropriate, will adhere to the guidelines - also note the documentation required relative to your investigation:

N.B Investigators must acknowledge, understand and adhere to all of the points on this checklist.

Project Title: Gestures for CAD interface – Pilot Study

Participants (staff/students carrying out investigation): PhD Student/Research Assistant Tijana Vuletic will carry out in the investigation. Participants will be PhD students from the department of Design, Manufacture and Engineering Management, University of Strathclyde

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It is the supervisor's responsibility to make students aware of these guidelines and the students to provide the supervisor with the required documentation from affected investigation components. Signed copies should be maintained by the supervisor and student(s) for departmental records.

☒ **Consent**. Obtain informed consent of all volunteers. A consent form must be signed by all volunteers.

☒ **Protection**. Protect all volunteers from possible harm and preserve their rights. No investigation should involve significant risks to mental or physical well-being of its participants.

☒ **Inducement**. Provide no financial inducement nor other coercion (actual or implied) to persuade people to take part in the investigation.

☒ **Withdrawal.** Volunteers must be free to withdraw at any stage, without giving reason.

☒ **Termination.** The investigation should stop immediately if volunteers report any problems (physical, mental or otherwise) during it. The problems must be reported to the appropriate ethics committee.

☒ **Recruitment.** Volunteer recruitment should wherever possible be via letter, notice (or orally - if through a group approach). However, random street or doorstep surveys are acceptable.

☒ **Staff Participation.** The motives for staff/students to participate as a volunteer in an investigation should be taken into special consideration i.e. neither declining nor agreeing to participate in an investigation should affect academic assessment in anyway.

☒ **Special Consideration**. Special consideration should be given to the young, adults with any cognitive disabilities or learning difficulties and to all persons who live in or are connected to an institutional environment (in such cases the investigator should refer to **Appendix C** of the 'code of practice on investigations on human beings').

☒ **Pregnancy.** Women of child bearing age must not be recruited for any investigation which could be harmful to fertility/pregnancy (in such cases the investigator should refer to **Appendix C** of the 'code of practice on investigations on human beings').

☒ **Selection.** Submissions based on the investigation should include details of the basis for volunteer selection i.e. questionnaires and/or other measures in the selection process.

☒ **Justification.** Investigators must justify the number/type of subjects chosen for each study.

☒ **Confidentiality.** Confidentiality and privacy must be maintained. Any waiver of confidentiality should be justified and consent must be given, in writing, by the volunteer(s). In addition, the investigator must comply with Data Protection Legislation.

☒ **Informing Volunteers.** Each volunteer must be provided with an information sheet providing full relevant details of the nature, object and duration of the proposed investigation and a contact for further queries (whom is independent of the investigation normally the secretary of the ethics advisory committee).

☒ **Deception.** There shall be no deception that might affect a person's willingness to participate in an investigation nor about the risks involved.

☒ **Unusual Symptoms.** Volunteers will be encouraged to note any unusual or unexpected symptoms arising during the investigation. These should be reported to the appropriate ethics committee

☒ **Location.** Places where investigations take place should be appropriate to the type and risk factor of study undertaken. Further, the ethics committee are entitled to carry out spot checks.

☒ **Records.** Full records of all procedures carried out should be maintained in an appropriate form. A register of all volunteers should be taken and a note of the population/sample from which they were drawn.

☒ **Queries.** Post investigation queries from a participant should be directed to an appropriate professional (supervisor, head of department etc.).

☒ **Insurance.** It is the responsibility for the applicant to seek extended insurance if the investigation scope falls out-with the University's Public Liability Policy (in such cases the investigator should refer to **Appendix B** of the original 'code of practice' document).

Additional general guidelines exist for biological, psychological and sociological investigations - in such cases refer to **Sections 6.2 and 6.3** of the original 'code of practice' document.

Supervisors Signature(s)

.... Date 9/8/17........

.... Date ....

Students/Researchers Signature(s)

.... Date 09/08/17........

.... Date ....

C 1.2 Ethics approval for the full study

Ethics Committee -
Code of Practice on Investigations on Human Beings

When implementing a staff or student project which involves 'investigation on human beings' it is important to note that the university has a code of practice governing the implementation and conduct of such investigations. This 'code of practice was developed by the 'Ethics Advisory Committee' and approved by the university court on 5th May 2000. The code governs all investigations on human beings including class teaching experiments and demonstrations, student projects and research investigations which fall within the scope of the code. The 'Departmental Research Committee' will act as the 'Departmental Ethics Committee', and can approve most routine, non-invasive investigations.

It is the responsibility of the supervisor to make the student aware of relevant guidelines and ensure that they are observed. The supervisor is also responsible for submitting details of proposed investigations for approval where necessary.

The following contains 2 checklists to aid the implementation of this practice:

(I) The first is to identify cases which require to be approved by the University Ethics Advisory Committee. If any of the boxes are marked in checklist (i) the investigation must be submitted to the university committee for approval.

(ii) The second is to ensure correct procedure is adhered to in any 'routine or non-invasive' investigation i.e. those which are readily approved by the 'Department Ethics Committee' (in essence the checklist represents a summary of Section 6 of the Code of Practice on Investigations on Human Beings.)

These checklists should not be viewed as a substitute for the original document and thus all supervisors should be familiar with the code before utilising these in staff/student research projects. The checklists are designed to ensure that the staff/students are immediately aware of the implications of the guidelines to their investigation. Furthermore, they act as departmental records of staff/student conduct in investigations on humans.

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In addition to the university regulations, investigations of a Physiological, Sociological and Biological nature must conform to additional 'codes of practice' set out by relevant professional bodies - in such cases the secretary of the ethics advisory board can supply copies of these statements.

(i) Supervisor and Student Ethics Checklist

Project Title: Gestures for CAD interface – Full Study

Participants (staff/students carrying out investigation): PhD Student/Research Assistant Tijana Vuletic will carry out in the investigation. Participants will be undergraduate, postgraduate and PhD students from the department of Design, Manufacture and Engineering Management, University of Strathclyde, professional designers, members of general public and potentially undergraduate and postgraduate students at Glasgow School of Art or University of Glasgow.

Investigation Content: Participants will be asked to observe an object being manipulated on a screen, and then asked to perform gestures which would lead to the same result. Participants will be recorded visually (using two cameras). Each individual session will take approximately 15-25 minutes. Participants will not be remunerated for their time.

Does the investigation involve any of the following (mark as appropriate):

1)	Harm, discomfort, physical or psychological risk (esp. pregnant women, elderly, the young).	yes ☐	no ☒
2)	Participants whose ability to give voluntary consent is limited (cognitively impaired, prisoners, persons with chronic physical or mental conditions).	yes ☐	no ☒
3)	Invasive techniques (DNA testing, collection of body fluids/tissue).	yes ☐	no ☒
4)	Extensive degree or duration of exercise or physical exertion.	yes ☐	no ☒
5)	Manipulation of human responses (cognitive or affective) which may involve stress or anxiety.	yes ☐	no ☒
6)	Administration of drugs, liquid/food additives.	yes ☐	no ☒
7)	Deception of the participants which might cause distress or effect their willingness to participate in the research.	yes ☐	no ☒
8)	The collection of highly personal, intimate, private or confidential information.	yes ☐	no ☒
9)	Payment to the participants (other than travel/time costs).	yes ☐	no ☒

If the answer to <u>any</u> of the above questions is yes you <u>must</u> submit a protocol to the 'Ethics Advisory Committee' unless previous consent has been granted for practising the 'generic' procedure involved. The protocol for such submissions to the 'Ethics Advisory Committee' can be found in Appendix A of the 'Code of Practice on Investigations of Humans Beings'.

Supervisors Signature(s)

.... Date ....15/1/18......

.... Date ....

Students/Researchers Signature(s)

.... Date ....15/01/18......

(ii) Checklist for Department Approved Investigations

Mark all boxes when you have read, understand and, where appropriate, will adhere to the guidelines - also note the documentation required relative to your investigation:

N.B Investigators must acknowledge, understand and adhere to all of the points on this checklist.

Project Title: Gestures for CAD interface – Full Study

Participants (staff/students carrying out investigation): PhD Student/Research Assistant Tijana Vuletic will carry out in the investigation. Participants will be undergraduate, postgraduate and PhD students from the department of Design, Manufacture and Engineering Management, University of Strathclyde, professional designers, members of general public and potentially undergraduate and postgraduate students at Glasgow School of Art or University of Glasgow.

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It is the supervisor's responsibility to make students aware of these guidelines and the students to provide the supervisor with the required documentation from affected investigation components. Signed copies should be maintained by the supervisor and student(s) for departmental records.

☒ **Consent**. Obtain informed consent of all volunteers. A consent form <u>must</u> be signed by all volunteers.

☒ **Protection**. Protect all volunteers from possible harm and preserve their rights. No investigation should involve significant risks to mental or physical well-being of its participants.

☒ **Inducement**. Provide no financial inducement nor other coercion (actual or implied) to persuade people to take part in the investigation.

☒ **Withdrawal.** Volunteers must be free to withdraw at any stage, without giving reason.

☒ **Termination.** The investigation should stop <u>immediately</u> if volunteers report any problems (physical, mental or otherwise) during it. The problems must be reported to the appropriate ethics committee.

☒ **Recruitment.** Volunteer recruitment should wherever possible be via letter, notice (or orally - if through a group approach). However, random street or doorstep surveys are acceptable.

☒ **Staff Participation.** The motives for staff/students to participate as a volunteer in an investigation should be taken into special consideration i.e. neither declining nor agreeing to participate in an investigation should affect academic assessment in anyway.

☒ **Special Consideration**. Special consideration should be given to the young, adults with any cognitive disabilities or learning difficulties and to all persons who live in or are connected to an institutional environment (in such cases the investigator should refer to **Appendix C** of the 'code of practice on investigations on human beings').

☒ **Pregnancy.** Women of child bearing age must not be recruited for any investigation which could be harmful to fertility/pregnancy (in such cases the investigator should refer to **Appendix C** of the 'code of practice on investigations on human beings').

☒ **Selection.** Submissions based on the investigation should include details of the basis for volunteer selection i.e. questionnaires and/or other measures in the selection process.

☒ **Justification.** Investigators must justify the number/type of subjects chosen for each study.

☒ **Confidentiality.** Confidentiality and privacy must be maintained. Any waiver of confidentiality should be justified and consent must be given, in writing, by the volunteer(s). In addition, the investigator must comply with Data Protection Legislation.

☒ **Informing Volunteers.** Each volunteer must be provided with an information sheet providing full relevant details of the nature, object and duration of the proposed investigation and a contact for further queries (whom is independent of the investigation normally the secretary of the ethics advisory committee).

☒ **Deception.** There shall be no deception that might affect a person's willingness to participate in an investigation nor about the risks involved.

☒ **Unusual Symptoms.** Volunteers will be encouraged to note any unusual or unexpected symptoms arising during the investigation. These should be reported to the appropriate ethics committee.

☒ **Location.** Places where investigations take place should be appropriate to the type and risk factor of study undertaken. Further, the ethics committee are entitled to carry out spot checks.

☒ **Records.** Full records of all procedures carried out should be maintained in an appropriate form. A register of all volunteers should be taken and a note of the population/sample from which they were drawn.

☒ **Queries.** Post investigation queries from a participant should be directed to an appropriate professional (supervisor, head of department etc.).

☒ **Insurance.** It is the responsibility for the applicant to seek extended insurance if the investigation scope falls out-with the University's Public Liability Policy (in such cases the investigator should refer to **Appendix B** of the original 'code of practice' document).

Additional general guidelines exist for biological, psychological and sociological investigations - in such cases refer to **Sections 6.2 and 6.3** of the original 'code of practice' document.

Supervisors Signature(s)

.... Date ..15\1\18.......

.... Date ....

Students/Researchers Signature(s)

.... Date ....

.... Date ..15/01/18.......

Appendix D – Pilot study 1 and 2 coding instructions

Coding instructions the coders were asked to adhere to during Pilot study 1 and Pilot study 2 coding.

D 1 Coding instructions

Please only code fields highlighted in yellow.

D 1.1 2D/3D

Gesture is 3D if hands "break" the plane (use more than the vertical plane the image is in).

D 1.2 Pinch

Thumb and pointer finger pinch the object or a part of it.

D 1.3 Grasp

Grasp is if at least one of the hands forms a picking up motion (hand closes over a part). Ignore gravitation or physicality of the object. Only look at the shape of the hand.

D 1.4 Point

At least one hand or finger points at a part.

D 1.5 Tap

At least one hand or finder taps a part (usually horizontally).

D 1.6 Flick

At least one hand or finger flicks away the part (or an element of it), waving it away usually with two fingers.

D 1.7 Open hand

At least one hand is open (palm open, fingers mostly straight).

D 1.8 Hand path coding

Static pose	Hand pose is held in one location
Dynamic pose	Hand pose changes in one location
Static pose and path	Hand pose is held as hand moves
Dynamic pose and path	Hand pose changes as hand moves
One-point hold	Static pose with one finger
One-point path	Static pose and path with one finger

D 1.9 Gesture type

Table 7 : Gesture type definitions

Type of gesture	**Definition**
Symbolic/Emblematic	Emblematic gestures represent a widely accepted meaning e.g. “thumbs up” (Wagner et al., 2014) Referential symbolic gestures represent “symbolic objects or concepts e.g. rubbing index finger and the thumb to refer to money” (Quek, 1995). Emblematic/Symbolic gestures - Devoid of any morphological relation with visual or logical referent. Have direct translation into words. Have a precise meaning known by a group, class or culture. Usually deliberately used to send a particular message. e.g. Hand waving as a greeting. (Rime & Schiaratura 1991)
Pantomimic/Mimetic	Mimetic act’ gestures represent familiar concepts, but they are pantomimes of what is being implied e.g. ”motioning ’lighting up’ of a cigarette to ask for a lighter” (Quek, 1995). Pantomime is “a sequence of gestures conveying a narrative, produced without speech” (Boulabiar et al., 2011). Play the role of the referent. E.g. To illustrate the words "He grasped a box", the speakers hands shape an imaginary box (Rime & Schiaratura, 1991)
Semaphoric	Semaphoric gestures are used to trigger a predefined action, defined in a formalised dictionary and therefore “require prior knowledge and learning” (Santos et al., 2016). They are “static poses or predefined stylized movements communicating an intended symbol to a machine” (Quek, 2004).

Type of gesture	Definition
Iconic (McNeill 85, 87) (similar - Physicographic (Effron 41/72), Motor primacy representational movements (Freedman 72), Illustrative (Cosnier 82), Illustrators (Ekman & Friesen)	Iconic gestures "represent meaning closely related to the semantic content of the speech"(Holler and Beattie, 2003, McNeill, 1985) and illustrate what is being said. For example, a person discussing an object rolling down a hill would perform a rolling motion using their hands. Present some figural representation of the object evoked in speech (Rime & Schiaratura, 1991).
Metaphoric (McNeil 85)(also Ideographs (Rime & Schiaratura, 1991)) (similar logicotopographic gestures (Efron 41/72))	Metaphoric gestures "are iconic gestures which represent abstract content" (Wagner et al., 2014, McNeill, 1992), e.g. a cutting gesture to indicate a decision has been made (Casasanto and Lozano, 2007). Sketch in space the logical track followed by the speaker's thinking. Parallel abstract thinking (Rime & Schiaratura, 1991).
Modalizing (Quek, 1995)/Speech linked (McNeill, 2006)/Speech marking (Rime & Schiaratura, 1991)/Beat (Wagner et al., 2014) (similar - batonlike (Efron 41/72), punctuating movements (Freedman 72), minor qualifiers (Freedman 72), batonic (McNeill 85, McNeill & Levy 82), batons (Ekman & Friesen 72), beats (McNeill 87), paraverbals (Cosnier 82))	Modalizing symbolic gestures primarily complement speech, but can also complement other means of communication. For example, a person asking "'Have you seen her husband?' while holding their hands apart would indicate he is overweight" (Quek, 1995). Speech marking - Stress some elements of speech for the sale of clarity. Parallel the introduction of some new element on the discourse. Chunk the sentence following the steps of the underlying reasoning (Rime & Schiaratura, 1991). Beat gestures are "simple and fast movements of hand that synchronize with prosodic events, variations in pitch, loudness, tempo, and rhythm, of speech" (Wagner et al., 2014).
Cohesive	Cohesive gestures are "those that are thematically related, but temporally separated", where a continuation of a specific theme after the speaker was interrupted is characterised by the recurrence of a gesture (Rautaray and Agrawal, 2015).
Butterworths/Adaptors	Butterworth's' were thought to be gestures that "arise as failures of speech e.g. hand grasping while a speaker is trying to recall a word" (McNeill, 1992). Adaptors "are gestures like headshaking or quickly moving one's leg that are unconscious and used to release body tension" (Rautaray and Agrawal, 2015).
Deictic	Deictic gestures are pointing gestures, used to indicate the direction of intended movement, or a direction of manipulation. Depending on the context and the direction of pointing, they can also have assigned meaning. Point toward some visually or symbolically present object (Rime & Schiaratura, 1991). Object might be a place or an event. Deictic gestures might represent an abstract form of iconic gestures (McNeill 87a)

D 1.10 Additional guide for gesture types used:

Pantomimic - If the real object would be interacted with the same way.

Iconic/Semaphoric – If more information required and the gesture performed could be misinterpreted without it.

Manipulative - If object being moved and the real object would be interacted with the same way.

Appendix E – Study coding instructions

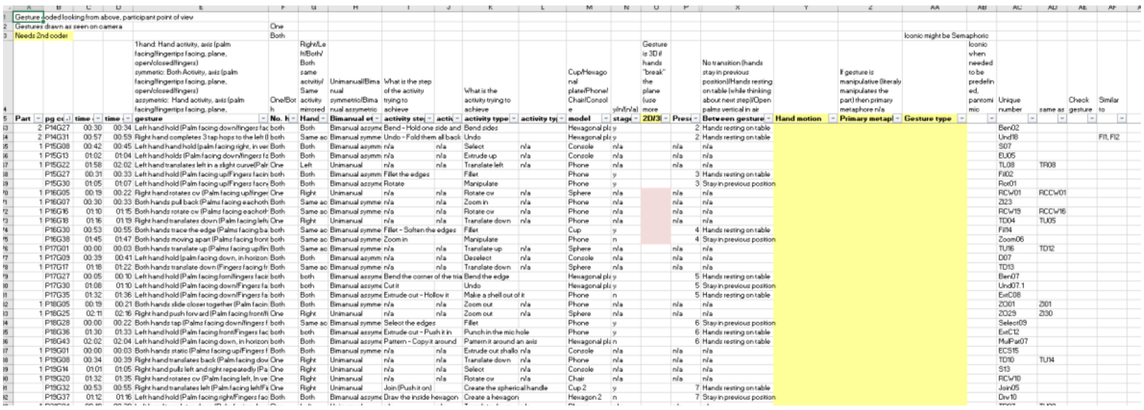
Coding instructions the coders were asked to adhere to during the full study coding.

E 1 Coding instructions

Thank you for agreeing to take part in the coding!

An excel table with codes is attached, shown in Figure 14, along with the sketches of gestures performed for each of the activities (same gestures are grouped, as indicated by the codes in the far right columns in the table, but otherwise not interpreted in any way). You can access all the videos of the gestures being performed, and sketches of them (in the zipped file) by following a Strathcloud link provided in the email (participants were sent a link with a link). Time stamps for the videos are in columns C and D, and should help you find them quickly.

Figure 14 : Screenshot of the excel file sent to the participants



A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	X	Y	Z	AA	AB	AC	AD	AE	AF
Gesture coded looking from above, participant point of view																								
Gestures drawn as seen on camera					One																			
Needs 2nd coder					Both														Iconic might be Semaphoric					
				1hand: Hand activity, axis (palm facing/fingertips facing, plane, open/closed/fingers) symmetic: Both Activity, axis (palm facing/fingertips facing, plane, open/closed/fingers) assymetric: Hand activity, axis (palm facing/fingertips facing, plane,	One/Both	Right/Left/Both/ Both same activity/ Same activity mirrored	Unimanual/Bimanual symmetric/Bimanual assymetric	What is the step of the activity trying to achieve		What is the activity trying to achieve		Cup/Hexagonal plate/Phone/ Chair/Console	y/n/(n/a)	Gesture is 3D if hands "break" the plane (use more		No transition (hands stay in previous position)/Hands resting on table (while thinking about next step)/Open palms vertical in air		If gesture is manipulative (literaly manipulates the part) then primary metaphore n/a		Iconic when needed to be predefined, pantomimic	Unique number	same as	Check gesture	Similar to
Part	**pg co**	**time**	**time**	**gesture**	**No. h**	**Hand**	**Bimanual et**	**activity ste**	**activ**	**activity type**	**activity ty**	**model**	**stage**	**2D/3**	**Pres**	**Between gesture**	**Hand motion**	**Primary metap**	**Gesture type**					
2	P14G27	00:30	00:34	Left hand hold (Palm facing down/fingers fac	both	Both	Bimanual assyme	Bend - Hold one side and		Bend sides		Hexagonal pl	y		2	Hands resting on table					Ben02			
2	P14G31	00:57	00:59	Right hand completes 3 tap hops to the left (I	both	Same ac	Bimanual symme	Undo - Fold them all back		Undo		Hexagonal pl	y		2	Hands resting on table					Und18			Fl1, Fl2
1	P15G08	00:42	00:45	Left hand hand hold (palm facing right, in ver	Both	Both	Bimanual asymm	n/a	n/a	Select	n/a	Console	n/a		n/a	n/a					S07			
1	P15G13	01:02	01:04	Left hand holds (Palm facing down/fingers fa	Both	Both	Bimanual asymm	n/a	n/a	Extrude up	n/a	Console	n/a		n/a	n/a					EU05			
1	P15G22	01:58	02:02	Left hand translates left in a slight curve(Palr	One	Left	Unimanual	n/a	n/a	Translate left	n/a	Phone	n/a		n/a	n/a					TL08	TR08		
	P15G27	00:31	00:33	Left hand hold (Palm facing up/Fingers facin	both	Both	Bimanual asymm	Fillet the edges		Fillet		Phone	y		3	Hands resting on table					Fil02			
	P15G30	01:05	01:07	Left hand hold (Palm facing up/Fingers facin	Both	Both	Bimanual assyme	Rotate		Manipulate		Phone	y		3	Stay in previous position					Rot01			
1	P16G05	00:19	00:22	Right hand rotates cw (Palm facing up/finger	One	Right	Unimanual	n/a	n/a	Rotate cw	n/a	Sphere	n/a		n/a	n/a					RCW01	RCCW01		
1	P16G07	00:30	00:33	Both hands pull back (Palms facing eachoth	Both	Same ac	Bimanual symme	n/a	n/a	Zoom in	n/a	Phone	n/a		n/a	n/a					ZI23			
1	P16G16	01:10	01:15	Both hands rotate cw (Palms facing eachoth	Both	Same ac	Bimanual symme	n/a	n/a	Rotate cw	n/a	Phone	n/a		n/a	n/a					RCW19	RCCW16		
1	P16G18	01:16	01:19	Right hand translates down (Palm facing left	One	Right	Unimanual	n/a	n/a	Translate down	n/a	Phone	n/a		n/a	n/a					TD04	TU05		
	P16G30	00:53	00:55	Both hands trace the edge (Palms facing ba	both	Same ac	Bimanual symme	Fillet - Soften the edges		Fillet		Cup	y		4	Hands resting on table					Fil14			
	P16G38	01:45	01:47	Both hands moving apart (Palms facing front	both	Same ac	Bimanual symme	Zoom in		Manipulate		Phone	n		4	Stay in previous position					Zoom06			
1	P17G01	00:00	00:03	Both hands translate up (Palms facing up/fin	Both	Same ac	Bimanual symme	n/a	n/a	Translate up	n/a	Sphere	n/a		n/a	n/a					TU16	TD12		
1	P17G09	00:39	00:41	Left hand hold (palm facing down, in horizon	Both	Both	Bimanual asymm	n/a	n/a	Deselect	n/a	Console	n/a		n/a	n/a					D07			
1	P17G17	01:18	01:22	Both hands translate down (Fingers facing fr	Both	Same ac	Bimanual symme	n/a	n/a	Translate down	n/a	Sphere	n/a		n/a	n/a					TD13			
	P17G27	00:05	00:10	Left hand hold (Palm facing forn/fingers faci	both	both	Bimanual assyme	Bend the corner of the tria		Bend the edge		Hexagonal pl	y		5	Hands resting on table					Ben07			
	P17G30	01:08	01:10	Left hand hold (Palm facing down/Fingers fa	both	both	Bimanual assyme	Cut it		Undo		Hexagonal pl	y		5	Stay in previous position					Und07.1			
	P17G35	01:32	01:36	Left hand hold (Palm facing down/Fingers fa	both	Both	Bimanual assyme	Extrude out - Hollow it		Make a shell out of it		Phone	n		5	Hands resting on table					ExtC08			
1	P18G05	00:19	00:21	Both hands slide closer together (Palm facin	Both	Both	Bimanual symme	n/a	n/a	Zoom out	n/a	Phone	n/a		n/a	n/a					ZO01	ZI01		
1	P18G25	02:11	02:16	Right hand push forward (Palm facing front/fi	One	Right	Unimanual	n/a	n/a	Zoom out	n/a	Sphere	n/a		n/a	n/a					ZO29	ZI30		
	P18G28	00:00	00:22	Both hands tap (Palms facing down/fingers f	both	Same ac	Bimanual symme	Select the edges		Fillet		Phone	y		6	Stay in previous position					Select09			
	P18G36	01:30	01:33	Left hand hold (Palm facing front/Fingers fac	both	both	Bimanual assyme	Extrude cut - Push it in		Punch in the mic hole		Phone	y		6	Hands resting on table					ExtC12			
	P18G43	02:02	02:04	Left hand hold (Palm facing down, in horizon	both	Both	Bimanual assyme	Pattern - Copy it around		Pattern it around an axis		Hexagonal pl	n		6	Hands resting on table					MulPat07			
1	P19G01	00:00	00:03	Both hands static (Palms facing up/Fingers f	Both	Both	Bimanual symme	n/a	n/a	Extrude cut shallo	n/a	Console	n/a		n/a	n/a					ECS15			
1	P19G08	00:34	00:39	Right hand translates back (Palm facing dov	One	Right	Unimanual	n/a	n/a	Translate down	n/a	Phone	n/a		n/a	n/a					TD10	TU14		
1	P19G14	01:01	01:05	Right hand pulls left and right repeatedly (Pa	One	Right	Unimanual	n/a	n/a	Select	n/a	Console	n/a		n/a	n/a					S13			
1	P19G20	01:32	01:35	Right hand rotates cw (Palm facing left, In ve	One	Right	Unimanual	n/a	n/a	Rotate cw	n/a	Chair	n/a		n/a	n/a					RCW10			
	P19G32	00:53	00:55	Right hand translates left (Palm facing left/Fi	One	Right	Unimanual	Join (Push it on)		Create the spherical handle		Cup 2	y		7	Hands resting on table					Join05			
	P19G37	01:12	01:16	Left hand hold (Palm facing right/Fingers fac	Both	Both	Bimanual assyme	Draw the inside hexagon		Create a hexagon		Hexagon 2	n		7	Stay in previous position					Drw10			

Only the fields highlighted in yellow and pale red are to be coded. These are:

- **2D/3D** (only 14 fields highlighted in pale red – for the rest the participants have stated they have imagined shapes as 3D objects suspended in front of them already).
- **Hand path** (fields highlighted in yellow in column Y)
- **Gesture type** (fields highlighted in yellow in column AA)

E 1.1 Description of the criteria for coding

E 1.1.1 2D/3D

Gestures should be coded as 2D if:

- All of the motions are performed in one plane that matches the plane gestures were shown in (vertical plane of the wall the screen was on), and users appear to be interacting with a touch screen.
- All of the motions are performed on the table (e.g. participant pushed the imaginary object forward with their palm touching the table).

Gestures should be coded as 3D if:

- Participants seem to interact with an object suspended in the air in front of them and use multiple planes with at least one part of the hand they use for the interaction with the object.
- Gestures are performed as if the imagined object is located on the table but is in 3D (e.g. hold the object's imaginary vertical axis and "rotate it" by touching the "sides of the object").

E 1.1.2 Hand path

Depending on motion of the hand a gesture can perform:

- Static pose – Hand and fingers are static. If both hands are used if at least one of the hands is moving the pose is considered to be dynamic.
- Dynamic pose – Hand does not move along a path, but fingers do move along their individual paths.
- Static pose and path – Hand and fingers assume a static shape and move along a path
- Dynamic pose and path – Hand and fingers change shape while moving along a path.

E 1.1.3 Gesture type

Gravity is not taken into account i.e. shape does not have weight; it is a virtual shape suspended in air.

Gestures can be:

- Pantomimic – If hands are performing the motions which would without any further information result in the activity performed.
- Metaphorical pantomimic - If hands are performing the motions which would without any further information result in a familiar activity, but not the activity performed because additional meanings were added to it.
- Iconic – If more information is needed to fully understand the gesture or it is ambiguous in any way i.e. if you would need to learn that that gesture indicates a certain activity.

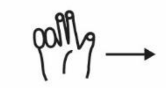
E 1.2 Examples of coded gestures

E 1.2.1 2D/3D examples

Gestures coded as 2D

- If all of the motions are performed in one plane that matches the plane gestures were shown in (vertical plane of the wall the screen was on), and users appear to be interacting with a touch screen. Example is given in Table 8.

Table 8 : 1st example of 2D gesture

	To translate an object left, hand is indication it is touching the vertical plane with one, two or three fingers. Gesture appears like it is interacting with a touch screen and it is not giving the object any depth.

- If all of the motions are performed on the table (e.g. participant pushed the imaginary object forward with their palm touching the table). Example is given in Table 9.

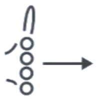
Table 9 : 2nd example of 2D gesture

	To translate up, gesture is sliding an imaginary object forwards, but is fully touching the table, not allowing for any other dimension for the object other than the front face in the vertical plane.

Gestures coded as 3D

- If participants seem to interact with an object suspended in the air in front of them. Example is given in Table 10.

Table 10 : 1st example of 3D gesture

	To translate an object left, right "side" of the object is pushed by the open palm, giving it depth**.**

- If gestures are performed as if the imagined object is located on the table but is in 3D. Example is given in Table 11.

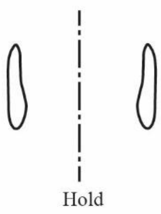
Table 11 : 2nd example of 3D gesture

	Gesture is sliding an imaginary object backwards to "translate down" in one plane, but the gesture is grasping the object in a plane perpendicular to it, using a plane that did not exist in the visual representation of the activity.

E 1.2.2 Hand path

- Static pose – Hand and fingers are static. If both hands are used if at least one of the hands is moving the pose is considered to be dynamic for that entire gesture. Example is given in Table 12.

Table 12 : Example of static pose

	To rotate both hands held in one pose.

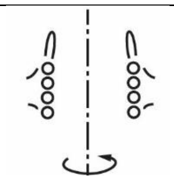
- Dynamic pose – Hand does not move along a path, but fingers do move along their individual paths. Example is given in Table 13.

Table 13 : Example of dynamic pose

	To zoom out hand turns from open palm into a full hand pinch, but stays in the same spot.

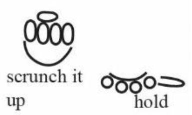
- Static pose and path – Hand and fingers assume a static shape and move along a path. Examples are given in Table 14.

Table 14 : Examples of static pose and path

	To rotate both hands follow a circular path, but the hand shape doesn't change.
	To zoom in both hands follow separate paths.

- Dynamic pose and path – Hand and fingers change shape while moving along a path. Examples are given in Table 15.

Table 15 : Examples of dynamic pose and path

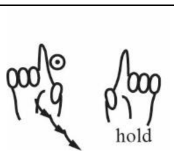
	To undo left hand holds, but right hand changes shape from open hand with palm facing up into a fist while moving upwards in the process.
	To zoom out, right hand moves forward, and transforms in the process from a fist into an open hand with the palm facing down

E 1.2.3 Gesture type

Gravity is not taken into account i.e. shape does not have weight, it is a virtual shape suspended in air.

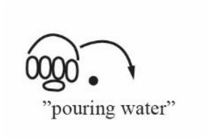
- Pantomimic (example given in Table 16).

Table 16 : Example of a pantomimic gesture

	To rotate left hand replaces an axis, and right hand spins the object around like a globe, or a basketball.

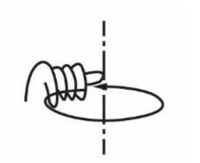
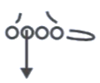
- Metaphorical pantomimic (example given in Table 17).

Table 17 : Example of metaphorical pantomimic gesture

	To lift the bottom of the cut higher up, water is poured so the level of "water" rises. It was never indicated that the water was in the cut, therefore additional meaning seems to have been added to the visual by the user.

- Iconic (examples given in Table 18).

Table 18 : Examples of iconic gestures

	To fillet an edge a hand traces it. While this may be considered to be a pantomimic gesture as you may form an edge of a sculpted cup that way, it may as well be just tracing a shape and to pick one of the two more information is needed.
	To translate an object down hand is moved downwards, parallel to the ground with an open palm. This may be understood as translate down, but it may also indicate change of height, compressing something, moving only one surface down etc. Without more information it is hard to say which option is more likely.

E 1.3 Suggested sequence to follow

E 1.3.1 2D/3D examples

- Is the gesture performed in more than one plane?
- Does the plane match the vertical plane, and does the full hand interact with that plane only?
- If all answers are yes then gesture is likely 2D. If any of the answers are no then gesture is likely 3D.

Flowchart to follow is given in Figure 15.

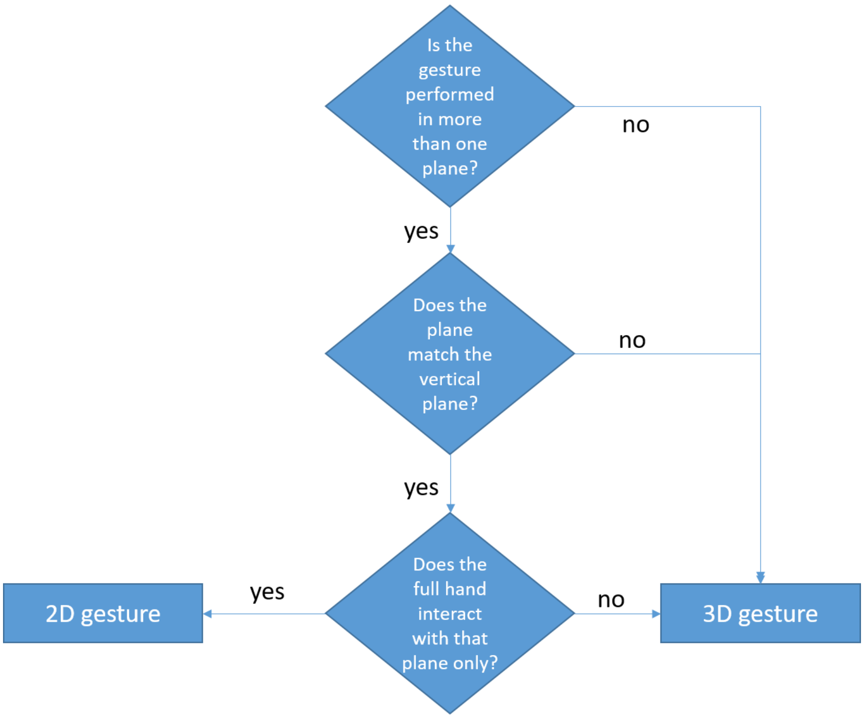


Figure 15 : Flowchart for the 2D/3D coding

E 1.3.2 Hand path

- Is at least one hand following a path of some kind?
- If the answer is yes the gesture is static pose and path or dynamic pose and path, depending on if the moving hand changes shape.
- If all hands used no not follow a path, do any of the fingers move? If so the gesture is dynamic pose.
- If the hands are completely static then the gesture is static pose.

Flowchart to follow is given in Figure 16.

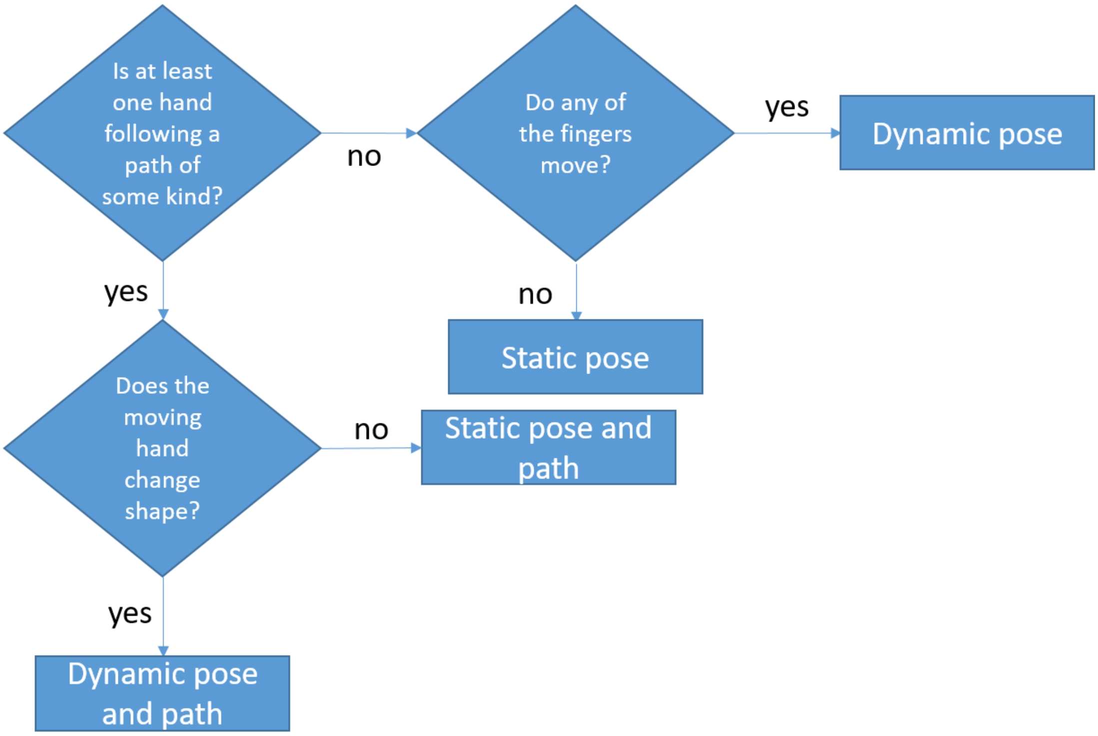


Figure 16 : Flowchart for the hand path coding

E 1.3.3 Gesture type

- Does the gesture seem to emulate an activity? If the answer is no Would gesture need to be learnt? If the answer is yes the gesture is iconic.
- If the answer is yes ask if more information needed to uniquely define the activity? Would gesture need to be learnt? If the answer is yes the gesture is iconic. If the answer is no the gesture may be pantomimic.
- If the gesture may be pantomimic - Ask if the gesture is actually performing the activity it is pantomiming. If the answer is yes then it is pantomimic. If the answer is no then the gesture is metaphorical pantomimic.

Flowchart is given in Figure 17.

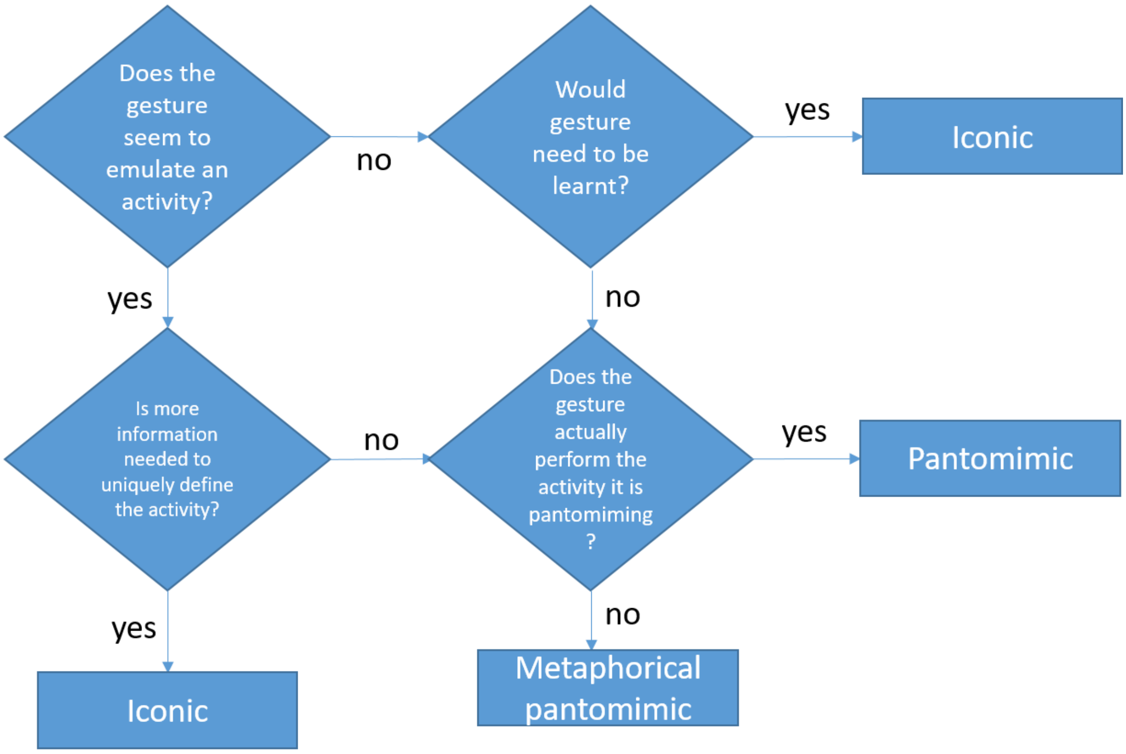
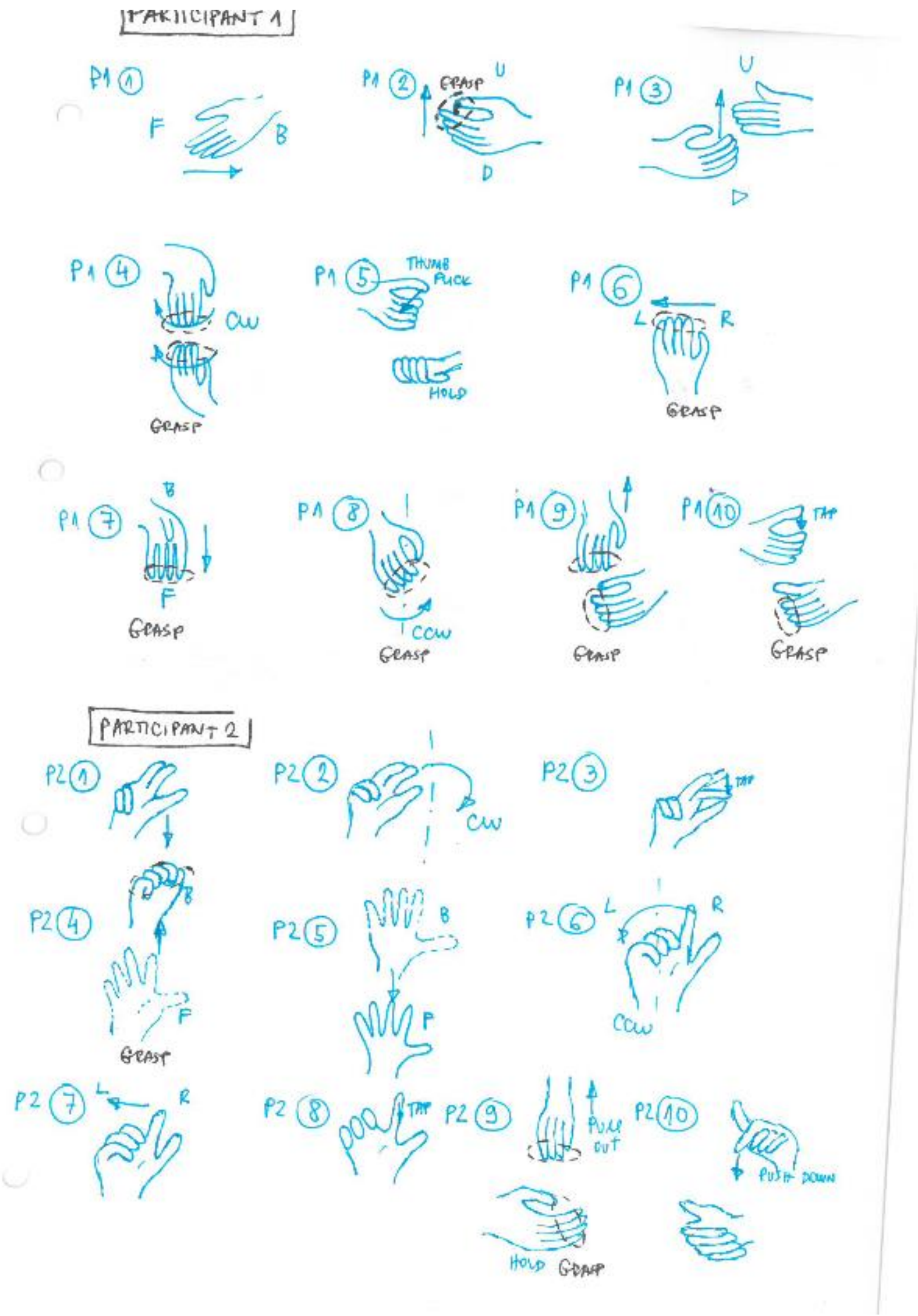


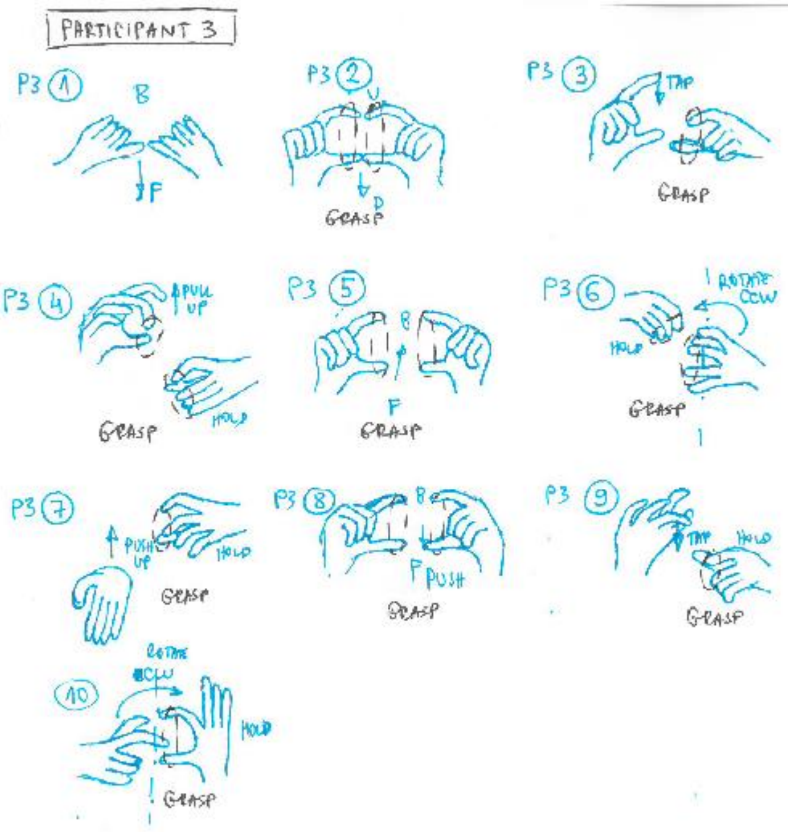
Figure 17 : Flowchart for the gesture type coding

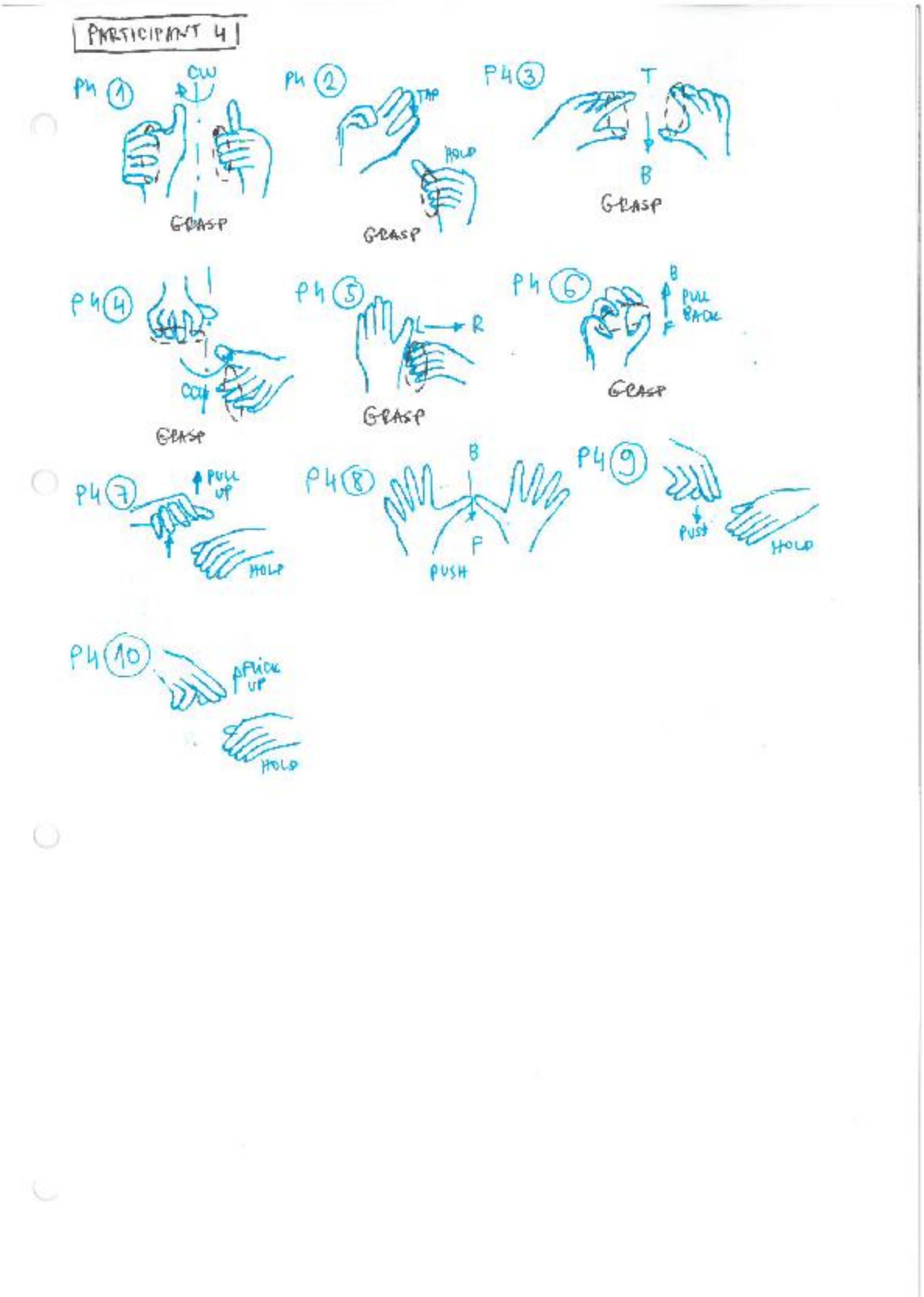
Appendix F- Gestures performed in the pilot studies

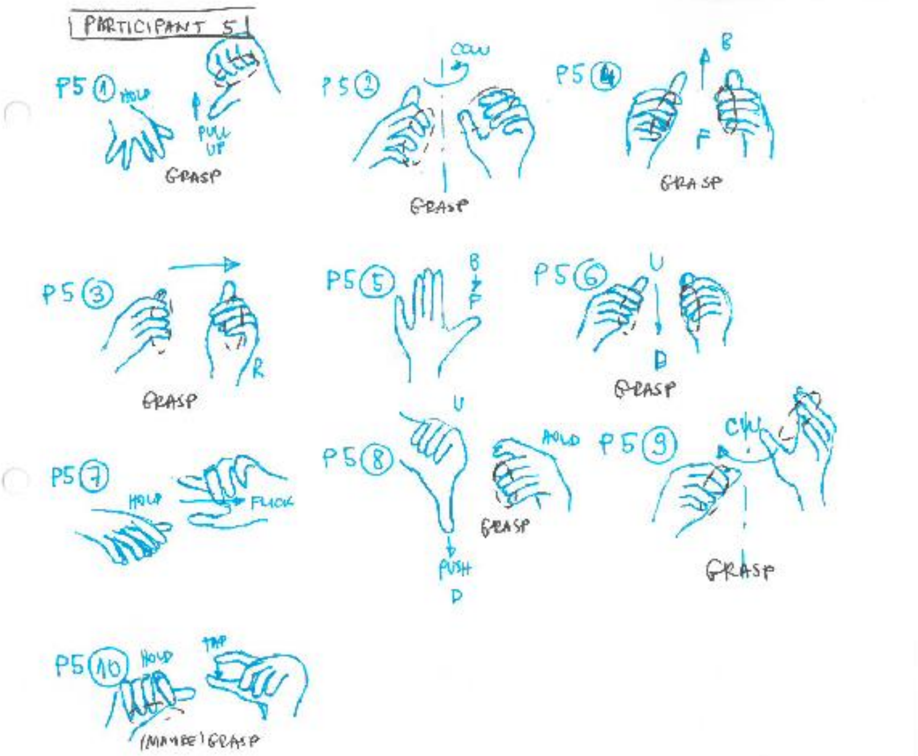
Appendix F contains gesture sketches from Pilot study 1 in Section F 1 and screenshots of gestures performed in Pilot study 2 in Section F 2.

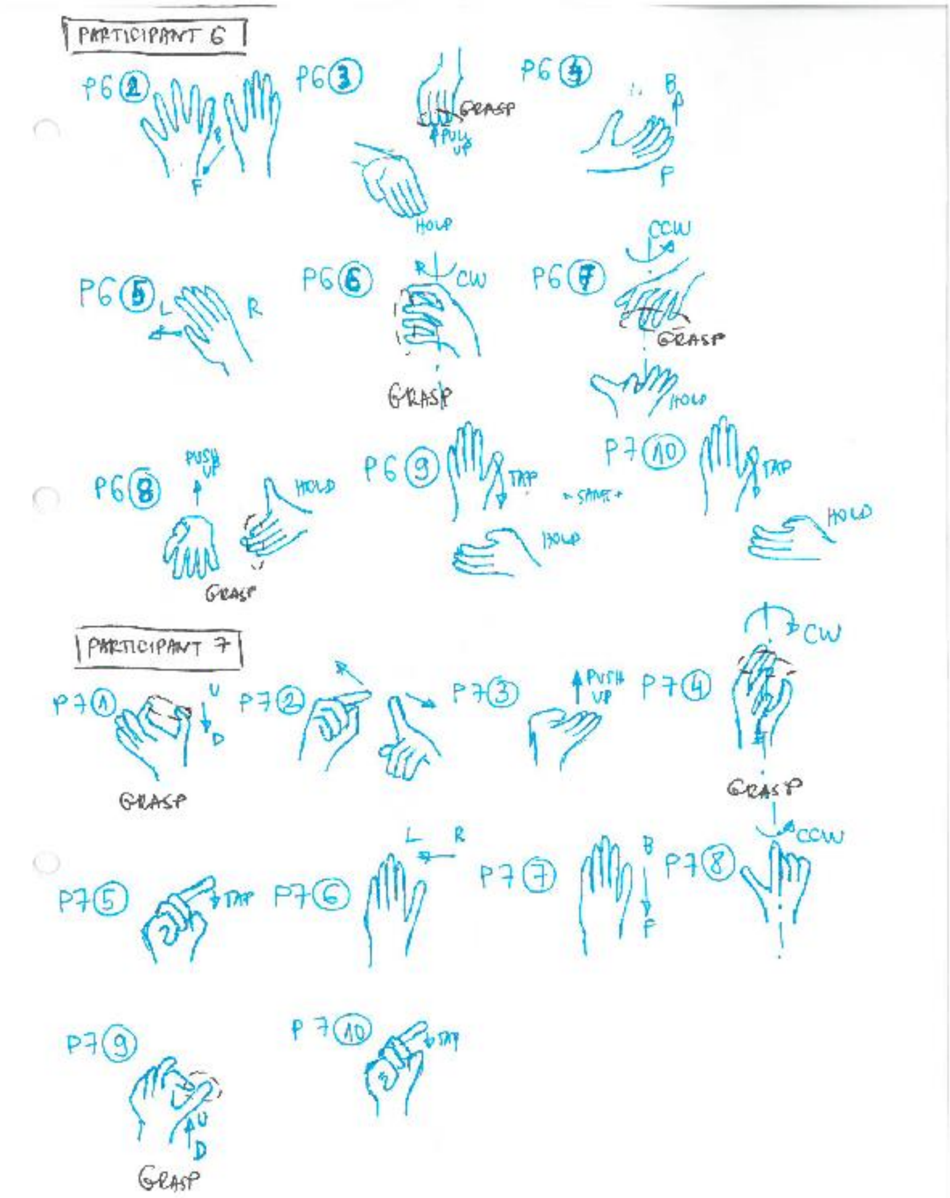
F 1 **Gestures from Pilot study 1**




PARTICIPANT 3
P3 1
B
F
P3 2
U
D
GRASP
P3 3
TAP
GRASP
P3 4
PULL UP
GRASP
HOLD
P3 5
B
F
GRASP
P3 6
ROTATE CCW
HOLD
GRASP
P3 7
PUSH UP
HOLD
GRASP
P3 8
B
F PUSH
GRASP
P3 9
TAP
HOLD
GRASP
10
ROTATE CW
HOLD
GRASP


PARTICIPANT 4
P4 1
CW
GRASP
P4 2
TAP
HOLD
GRASP
P4 3
T
B
GRASP
P4 4
CCW
GRASP
P4 5
L
R
GRASP
P4 6
B
F
PULL BACK
GRASP
P4 7
PULL UP
HOLD
P4 8
B
F
PUSH
P4 9
PUSH
HOLD
P4 10
PICK UP
HOLD


PARTICIPANT 5
P5 1
HOLD
PULL UP
GRASP
P5 2
CCW
GRASP
P5 4
B
F
GRASP
P5 3
R
GRASP
P5 5
B
F
P5 6
U
D
GRASP
P5 7
HOLD
FLICK
P5 8
U
HOLD
GRASP
PUSH
D
P5 9
CW
GRASP
P5 10
HOLD
TAP
(MAYBE) GRASP


PARTICIPANT 6
P6 ②
P6 ③
GRASP
PULL UP
HOLD
P6 ④
B
F
P6 ⑤
L
R
P6 ⑥
CW
GRASP
P6 ⑦
CCW
GRASP
HOLD
P6 ⑧
PUSH UP
HOLD
GRASP
P6 ⑨
TAP
HOLD
P7 ⑩
TAP
HOLD
PARTICIPANT 7
P7 ①
U
D
GRASP
P7 ②
P7 ③
PUSH UP
P7 ④
CW
GRASP
P7 ⑤
TAP
P7 ⑥
L
R
P7 ⑦
B
F
P7 ⑧
CCW
P7 ⑨
U
D
GRASP
P7 ⑩
TAP

F 2 **Gestures from Pilot study 2**

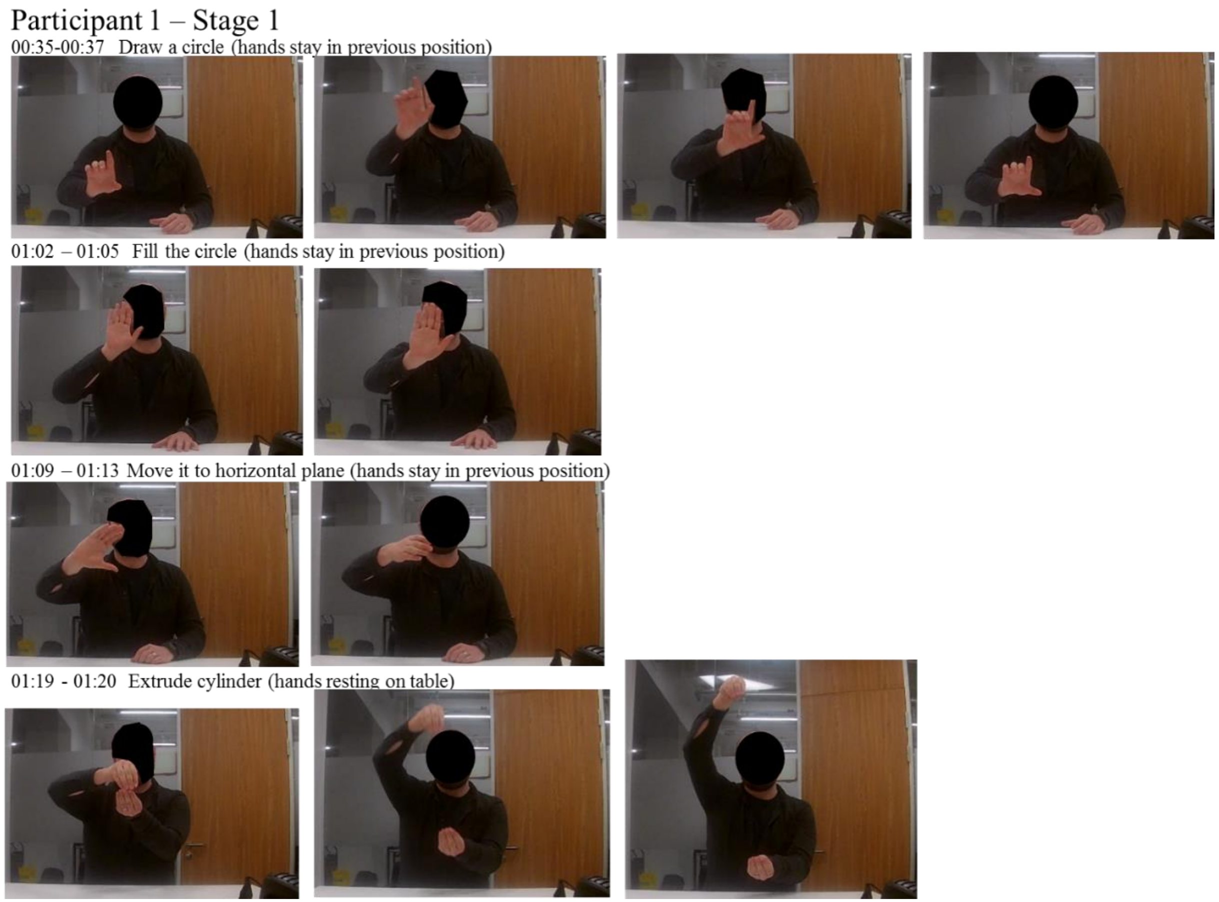


Figure 18 : Participant 1 - Stage 1 Part 1

01:42-01:44 Reorient so I'm looking at a circular profile (hands stay in previous position)

01:48– 01:50 Draw a circle (hands stay in previous position)

01:59 – 02:01 Adjust the size of wall thickness (hands stay in previous position)

02:03 – 02:11 Push in to hollow (hands resting on table)

Figure 19 : Participant 1 - Stage 1 part 2

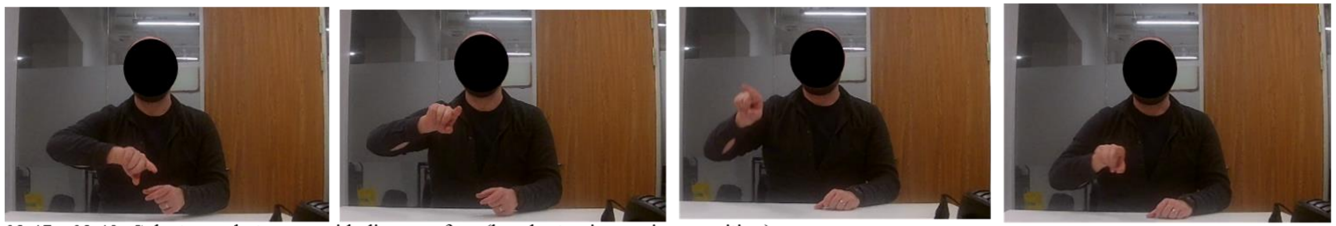
02:45– 02:46 Select top surface (hands stay in previous position)

02:52 – 02:55 Fillet the edge (hands resting on table)

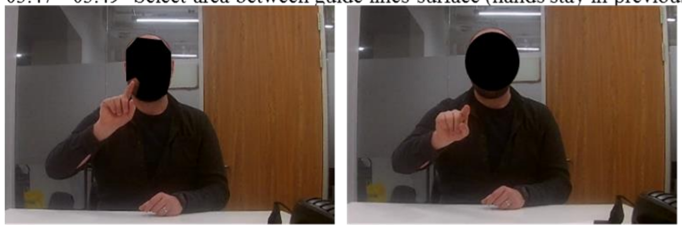
03:14 – 03:16 Create a plane to draw the handle in (hands resting on table)

Figure 20 : Participant 1 - Stage 1 part 3

03:31-03:33 Draw handle guide lines surface (hands stay in previous position)



03:47– 03:49 Select area between guide lines surface (hands stay in previous position)



03:54 – 03:56 Give it thickness (hands stay in previous position)

04:01 – 04:03 Select handle (hands stay in previous position)

04:07-04:11 Smooth handle (hands resting on table)

Figure 21 : Participant 1 - Stage 1 part 4

Participant 1.1 second activity

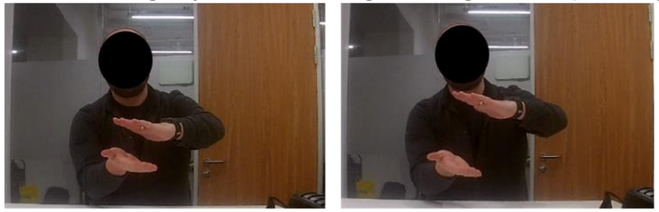
04:42 – 04:43 Draw a hexagon (hands resting on table)

05:05 – 05:07 Indicate that it's origin plane is actually horizontal (hands stay in previous position)

05:12 – 05:14 Create a second plane (hands stay in previous position)

Figure 22 : Participant 1 - Stage 2 part 1

05:34 – 05:36 Specify distance between planes and parallelism (hands stay in previous position)



05:42 – 05:44 Copy existing sketch to new plane (hands stay in previous position)

06:00 – 06:05 Scale sketch (hands resting on table)

06:20 – 06:24 Create and edge (hands stay in previous position)

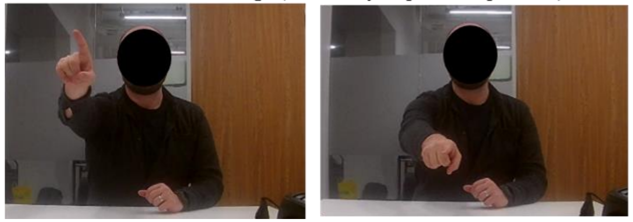


Figure 23 : Participant 1 - Stage 2 part 2

06:32 – 06:35 Create an axis (hands stay in previous position)

06:53 – 06:54 Select axis (hands resting on table)

06:56 – 06:58 Pattern edge around the axis (hands stay in previous position)

07:18 – 07:20 Fill in surface (hands stay in previous position)

07:26 – 07:29 Extrude part to give it thickness (hands resting on table)

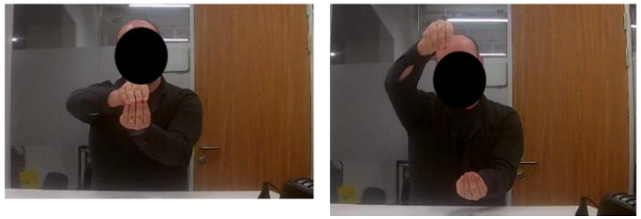


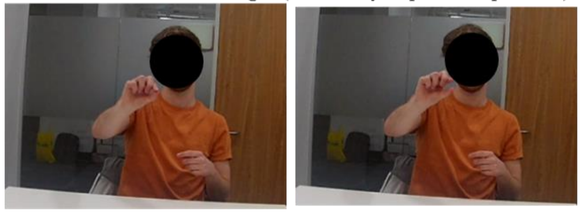
Figure 24 : Participant 1 - Stage 2 part 3

Participant 2 - Stage 1

00:31-00:35 Draw a triangle in a vertical plane (hands stay in previous position)

00:39 – 00:41 Select the triangle (hands stay in previous position)

00:41 – 00:45 Extrude triangle (hands stay in previous position)



00:46 - 00:48 Hold the shape (hands stay in previous position)

Figure 25 : Participant 2 - Stage 1 part 1

00:51-00:53 Bend the corner of the triangle (hands stay in previous position)

00:54– 00:56 Trace the bend edge to define it (hands resting on table)

01:24 – 01:27 Constrain the triangle in the middle (hands stay in previous position)

01:27 – 01:29 Select the edge on the far end (hands stay in previous position)

01:30-01:35 Rotate it all the way around (hands stay in previous position)

01:37– 01:38 Confirm the end of rotation (hands resting on table)

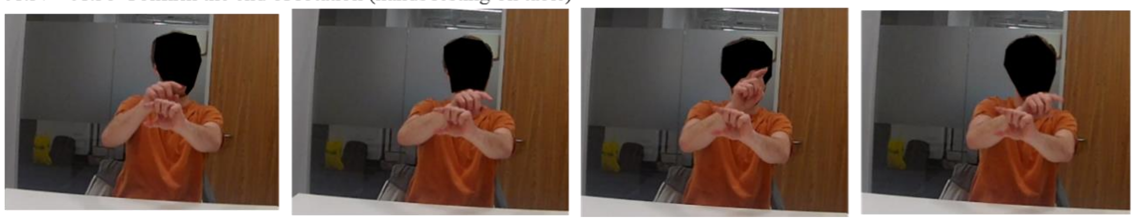


Figure 26 : Participant 2 - Stage 1 part 2

Figure 27 : Participant 2 - Stage 2 part 1

02:08 – 02:11 Get rid of that (hands stay in previous position)

02:14 – 02:16 Round the edges at one point (hands resting on table)

02:16 – 02:18 Round the edges around the full edge (hands stay in previous position)

02:24 – 02:25 Turn the cup face on (hands stay in previous position)

02:27 – 02:28 Select the plane that sits in the middle (hands stay in previous position)

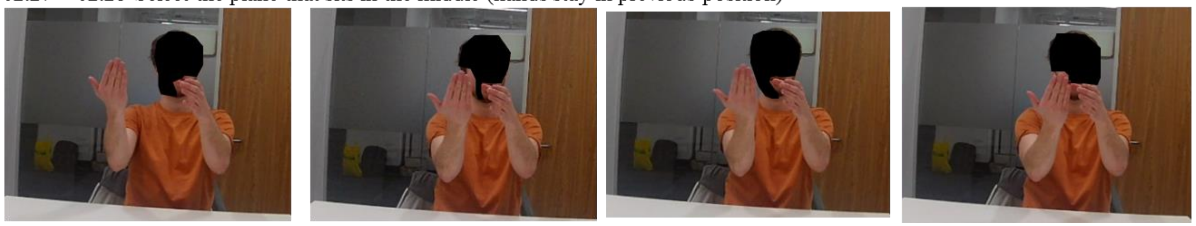


Figure 28 : Participant 2 - Stage 2 part 2

02:31 – 02:33 Draw the handle shape (hands resting on table)

02:42 – 02:43 Select the end of the loop (hands stay in previous position)

02:43 – 02:44 Draw a little circle (hands stay in previous position)

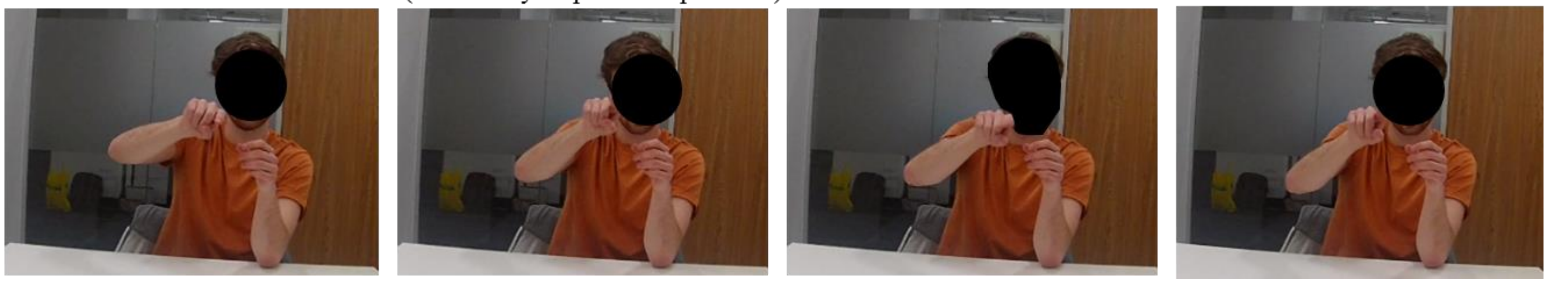


Figure 29 : Participant 2 - Stage 2 part 3

Participant 3 – Stage 1

00:25-00:27 I'm going to draw a rectangle (hands stay in previous position)

00:28 – 00:29 Then I'm going to extrude it slightly (hands resting on table)

00:34 – 00:35 Then I'm going to select the corners (hands stay in previous position)

00:36 - 00:38 …And change radius of them (hands resting on table)

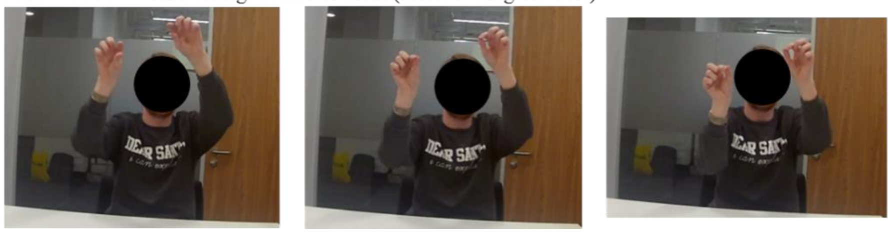
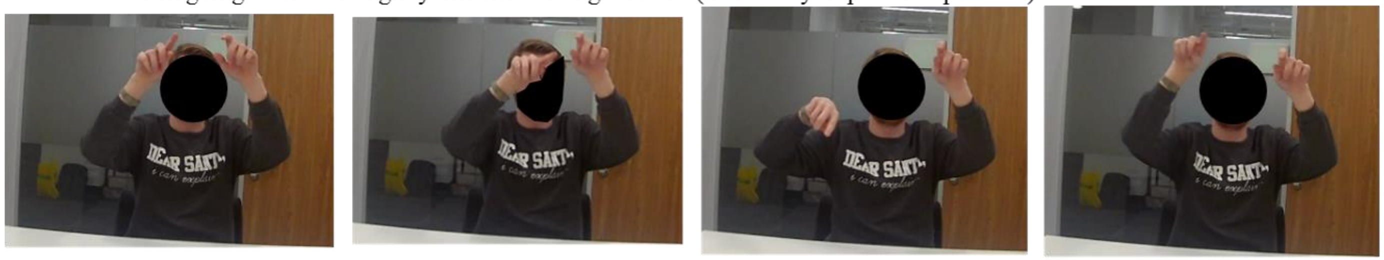


Figure 30 : Participant 3 - Stage 1 part 1

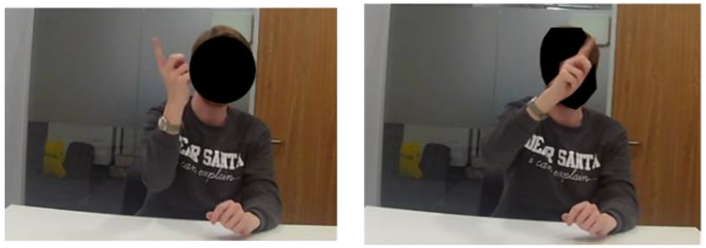
00:41-00:44 I'm going to draw a slightly smaller rectangle inside (hands stay in previous position)



00:45– 00:48 I'm going to adjust the thickness of it (hands resting on table)

00:56 – 00:58 I'm going to grab the corners of it and pull it apart and make it slightly bigger (hands resting on table)

01:08 – 01:09 I'm going to use my finger to move it around



01:10-01:11 To zoom in I'll use both fingers to push in and out (hands resting on table)

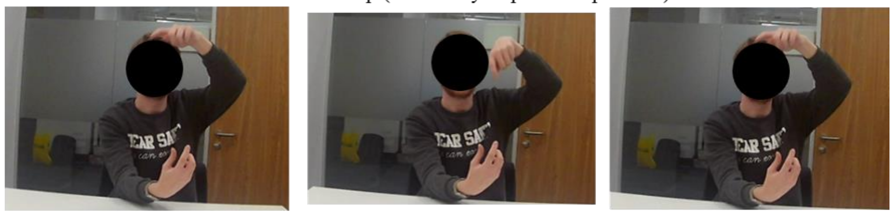
Figure 31 : Participant 3 - Stage 1 part 2

Participant 3 – Stage 2

01:22 – 01:23 Draw a circle at the bottom (hands stay in previous position)

01:24 – 01:26 and extrude it (hands stay in previous position)

01:28 – 01:29 Draw another circle on top (hands stay in previous position)



01:29 – 01:30 and extrude it down (hands stay in previous position)

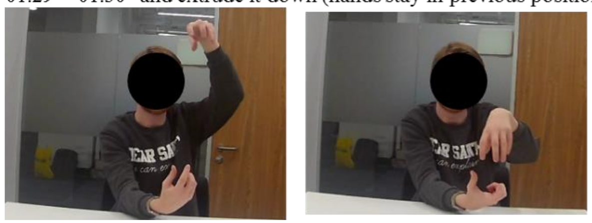
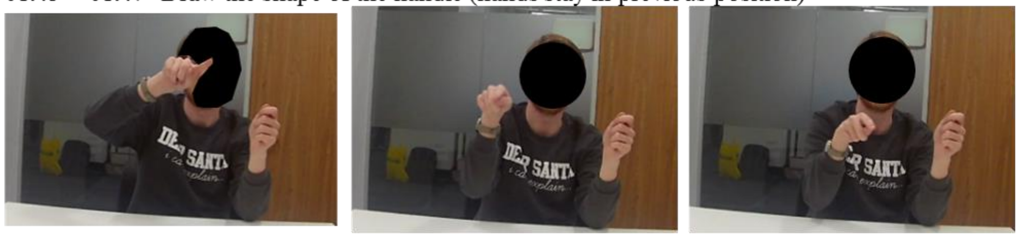


Figure 32 : Participant 3 - Stage 2 part 1

01:35 – 01:36 Touch the top with my finger to smooth it off (hands stay in previous position)

01:42 – 01:43 On the side I'm going to move it to the plane I need it to be in (hands stay in previous position)

01:45 – 01:47 Draw the shape of the handle (hands stay in previous position)



02:00 – 02:01 Draw a circle (hands stay in previous position)

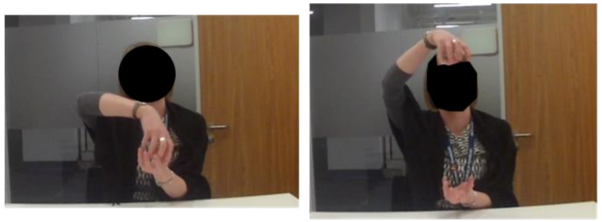
02:01 – 02:02 And pull it around (hands resting on table)

Figure 33 : Participant 3 - Stage 2 part 2

Participant 4 - Stage 1

00:22-00:23 draw a circle (hands stay in previous position)

00:23 – 00:29 Then extrude it (hands resting on table)



00:29 – 00:32 draw the circle on the top of the cylinder(hands stay in previous position)

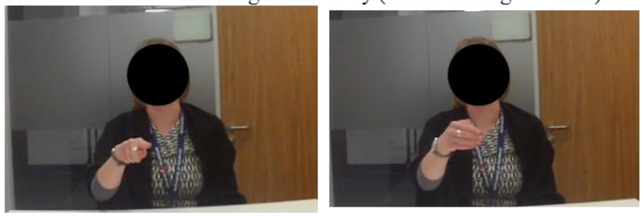
00:34 - 00:38 Then push it down (hands resting on lap)

Figure 34 : Participant 4 - Stage 1 part 1

00:45-00:47 Touching the edge if the cylinder (hands resting in lap)

00:57– 00:58 draw a half circle (hands stay in previous position)

00:58 – 00:59 Connecting to the body (hands resting on table)



01:05 – 01:09 zoom in (hands resting in lap)

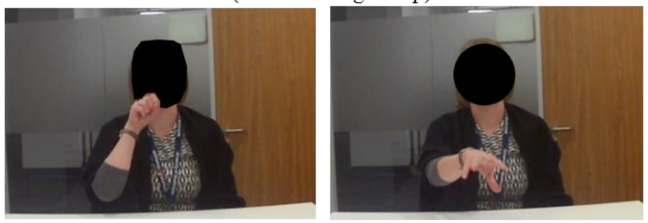


Figure 35 : Participant 4 - Stage 1 part 2

Participant 4 - Stage 2

01:28 – 01:36 Pull out to make the rectangle shape (hands stay in previous position)

01:38 – 01:43 pull down slightly to give it depth (hands resting in lap)

01:51 – 01:29 Cut it out with my hands resting in lap)

Figure 36 : Participant 4 - Stage 2 part 1

Figure 37 : Participant 5 - Stage 1 part 1

00:56-00:57 Zoom in (hands resting on the table)

01:23– 01:30 multiply it 6 times (hands stay in previous position)

Only 2 repetitions shown here

01:30 – 01:31 the arrange them around (hands resting on table)

Figure 38 : Participant 5 - Stage 1 part 2

Participant 5 – Stage 2

01:43 – 01:46 Draw a rectangle (hands stay in previous position)

01:47 – 01:52 Round the sides (hands stay in previous position)

01:56 – 01:57 Extrude it (hands stay in previous position)

Figure 39 : Participant 5 - Stage 2 part 1

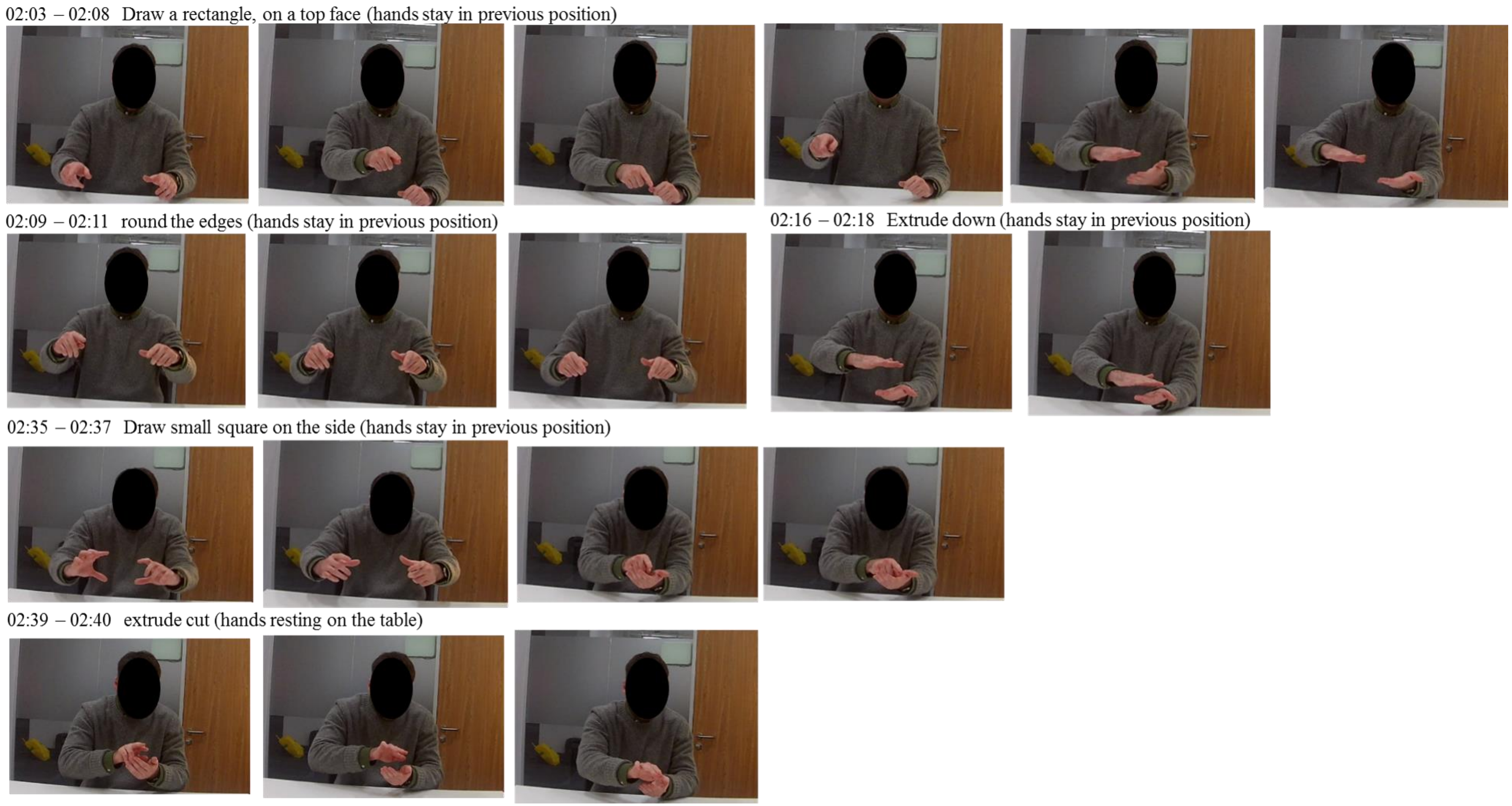
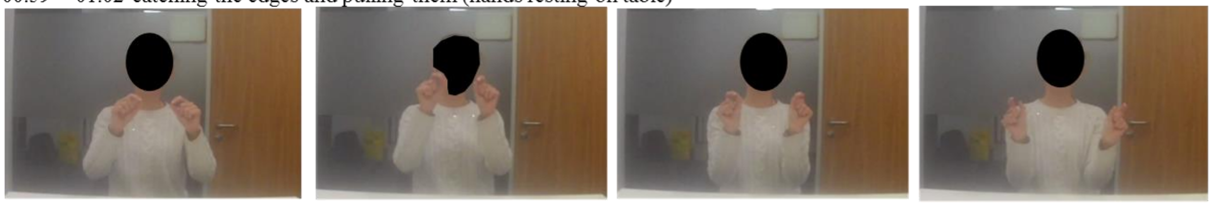


Figure 40 : Participant 5 - Stage 2 part 2

Figure 41 : Participant 6 - Stage 1 part 1

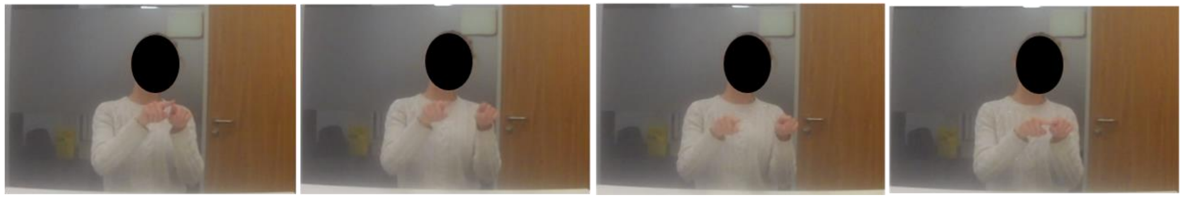
00:59 – 01:02 catching the edges and pulling them (hands resting on table)



01:07 – 01:08 zoom in (hands stay in previous position)

01:09 – 01:11 The on the bottom surface (turn it around) (hands stay in previous position)

01:12 – 01:13 Cutting a hole (hands stay in previous position)



01:13 – 01:14 And taking it out (hands resting in lap)

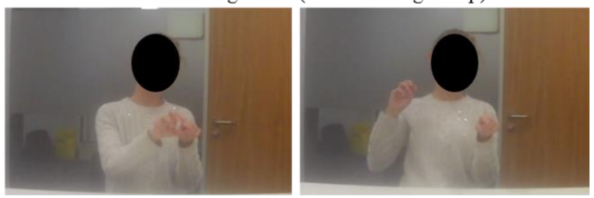


Figure 42 : Participant 6 - Stage 1 part 2

Participant 6 – Stage 2

01:21 – 01:22 I'd make a line (hands stay in previous position)

02:09 – 02:11 Grab the middle bit and pull it out (hands stay in previous position)

02:29 – 02:30 And I want it to fold along these lines (hand resting in lap)

Figure 43 : Participant 6 - Stage 2 part 1

Appendix G- Full study details

Appendix G contains information about:

- Participants and their details, order of study Part 1 and Part 2 performance and questionnaire answers (Section G 1),
- Lists of sequences in the study Part 1 in each of the videos (Section G 2),
- Sketches of gestures performed in the Full study (Part 1 and Part 2) (Section G 3),
- Gesture key (Section G 4),
- Categorised gestures and the codes assigned to them (Section G 5),
- Comparison of gestures performed by the same participants for different objects during the same activities (Section G 6).

G 1 Participants and their details, order of study Part 1 and Part 2 performance and questionnaire answers

Information on participants and their details is given in Table 19. Information of order of study Part 1 and Part 2 performance and questionnaire answers is given in Table 20.

Table 19 : Participants and their details

Participant number	Gender	Age	Occupation	Department	Degree	Year of study	Previous department	Previous degree	Highest degree awarded	Duration of study	Additional notes	CAD software used in the past	No of years	Years of design experience	Handedness
1	male	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks, Creo	3	0	Right
2	female	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks	2.5	0	Right
3	male	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks, Inventor	6	4	Right
4	male	24	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks	3	0	Right
5	female	20	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks, Autocad Inventor	6	3	Right
6	male	25	Product designer/CAD operator	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Solidworks/Fusion 360	6	2	Right
7	female	23	Student	Engineering - GLA + GSA	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks, Inventor	5	6 months	Right
8	female	23	Student	Science & Engeineering	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks	2	0	Right
9	male	20	Student	DMEM	PDE	2	n/a	n/a	n/a	n/a	n/a	Solidworks, Autodesk Inventor	3	0	Right
10	female	23	Student	Engineering - GLA + GSA	PDE	4	n/a	n/a	n/a	n/a	n/a	Solidworks	3	0	Right

Participant number	Gender	Age	Occupation	Department	Degree	Year of study	Previous department	Previous degree	Highest degree awarded	Duration of study	Additional notes	CAD software used in the past	No of years	Years of design experience	Handedness
11	male	23	Student	DMEM	PDE	4	-	-	-	-	-	Solidworks, Inventor, Rhino/Grasshopper	6	3 months	Left
12	male	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks	2	0	Right
13	female	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks, ProDesktop	5	0	Right
14	female	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	AutoCAD	3	6	Right
15	male	22	Student	DMEM	PDE	4	n/a	n/a	n/a	n/a	n/a	Solidworks, AutoCAD	7	2	Right
16	female	33	Student	DMEM	PDE	4	Architecture	Bachelor of Environmental Design	B. Env. Des	5 years	University of Manitoba	Solidworks, AutoCAD, Inventor, Rhino, Sketchup, Revit	8	3	Right, Ambidextrous with mouse
17	male	41	Engineer	n/a	n/a	n/a	n/a	DMEM	MSc	1	n/a	Solidworks, Autocad, Smartplant3D, Catia	10	10	Right
18	male	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks, Autodeks	5	0	Right
19	female	24	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks, Creo	5	3	Right
20	male	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks, Inventor	5	0	Right

Participant number	Gender	Age	Occupation	Department	Degree	Year of study	Previous department	Previous degree	Highest degree awarded	Duration of study	Additional notes	CAD software used in the past	No of years	Years of design experience	Handedness
21	male	21	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks, Inventor	5	0	Left
22	female	23	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks, Rhino	5	0	Right
23	female	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks	4	7	Right
24	female	21	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks	4	0	Right
25	male	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks, Edgecam, NX9	4.5	0	Right
26	female	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks	4	3 months	Right
27	male	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks	4	0	Right
28	male	20	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks	7	4	Right
29	female	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks	4	0	Right
30	female	21	Student	SMEM	PDE	4	n/a	n/a	n/a	n/a	n/a	Solidworks, ProEngineer	5	0	Right
31	male	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks	4	2 months	Right
32	male	22	Student	DMEM	PDE	4		Civil Engineering - Brazil				Solidworks	2	0	Right
33	male	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks, Inventor, Alias	5	3	Right

Participant number	Gender	Age	Occupation	Department	Degree	Year of study	Previous department	Previous degree	Highest degree awarded	Duration of study	Additional notes	CAD software used in the past	No of years	Years of design experience	Handedness
34	male	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks	5	0	Left
35	male	21	Student	DMEM	PDE	4	n/a	n/a	n/a	n/a	n/a	Solidworks, Inventor	3	0	Right
36	male	20	Student	DMEM	PDE	4	n/a	n/a	n/a	n/a	n/a	Solidworks	4	1	Left
37	male	21	Student	DMEM	PDE	4	n/a	n/a	n/a	n/a	n/a	Solidworks, Autodesk Fusion, Autodesk Inventor	6	3 months	Left
38	male	22	Student	DMEM	PDE	5	n/a	n/a	n/a	n/a	n/a	Solidworks, Autodesk, rhino	7	2	Right
39	male	21	Student	DMEM	PDE	4	n/a	n/a	n/a	n/a	n/a	Solidworks, Autodesk Inventor	6	2	Right
40	male	20	Student	DMEM	PDE	4	n/a	n/a	n/a	n/a	n/a	Solidworks, Autodesk	5	1	Right
41	male	20	Student	DMEM	PDE	4	n/a	n/a	n/a	n/a	n/a	AutoCAD, Inventor, Solidworks	8	0	Left
42	male	22	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks	2.5	0	Right
43	male	27	Student	School of Design, GSA & Glasgow University	PDE MSc	1	School of engineering (Aristotle University)	Electronics and Systems Engineering	Diploma (Meng equivalent)	5 years		Solidworks	3	1	Right

Participant number	Gender	Age	Occupation	Department	Degree	Year of study	Previous department	Previous degree	Highest degree awarded	Duration of study	Additional notes	CAD software used in the past	No of years	Years of design experience	Handedness
44	male	20	Student	DMEM	PDE	3	n/a	n/a	n/a	n/a	n/a	Solidworks, Autodesk Inventor	6.5	6 (started design subjects in 1st year of HS)	Left

Table 20 : Participants, video and presentation details, and order of study Part 1 and Part 2 of the study were performed

	Gestures		
Participant number	**Part 1 – video number**	**Part 2 – presentation number**	**Study part performed first**
1	1	1	Part 1
2	2	2	Part 2
3	3	3	Part 1
4	4	4	Part 1
5	5	5	Part 2
6	6	6	Part 1
7	7	2	Part 2
8	8	1	Part 1
9	9	3	Part 2
10	10	4	Part 1
11	1	5	Part 2
12	2	6	Part 1
13	3	1	Part 2
14	4	2	Part 1
15	5	3	Part 2
16	6	4	Part 1
17	7	5	Part 2
18	8	6	Part 2
19	9	7	Part 1
20	10	8	Part 1
21	1	7	Part 1
22	2	8	Part 2
23	3	1	Part 2
24	4	3	Part 2
25	5	2	Part 1
26	6	4	Part 2
27	7	5	Part 1
28	8	6	Part 2
29	9	7	Part 1
30	10	7	Part 2
31	1	8	Part 1
32	2	8	Part 2
33	3	7	Part 1
34	4	8	Part 2
35	5	1	Part 1
36	6	2	Part 2
37	7	3	Part 1

38	8	4	Part 2
39	9	5	Part 1
40	10	6	Part 2
41	1	7	Part 1
42	4	4	Part 2
43	7	5	Part 1
44	1	7	Part 2

Table 21 : Participants and their questionnaire answers

Participant number	Did you imagine the objects shown as 3D objects suspended in air in front of you?	Were you tempted to use gestures you use to interact with your phone or tablet?	Did the shape of the object influence the gestures you made?	Had the phone been a rectangular box, would you interact with it the same way?	Did you struggle with any actvities and if so which?
1	Agree	Disagree	Strongly agree	Don't know	No problems
2	Agree	Strongly agree	Strongly agree	Disagree	Originally I struggled to understand what I was to do for the first part, but once I began it was fine
3	Strongly agree	Strongly agree	Strongly agree	Agree	No problems
4	Strongly agree	Strongly agree	Strongly agree	Agree	Rotating objects I felt I wanted to use both arms to spin it but felt I couldn't move my arms enough to get the right effect
5	Strongly agree	Strongly agree	Agree	Agree	The last one, making the shapes and thinking of the gestures that would mean different buttons.
6	Agree	Agree	Agree	Agree	More complex actons like increasing wall thickness, polygon shape
7	Strongly agree	Strongly agree	Strongly agree	Strongly agree	Rotating as it was difficult to indicate

Participant number	Did you imagine the objects shown as 3D objects suspended in air in front of you?	Were you tempted to use gestures you use to interact with your phone or tablet?	Did the shape of the object influence the gestures you made?	Had the phone been a rectangular box, would you interact with it the same way?	Did you struggle with any actvities and if so which?
					axis and direction of rotation
8	Agree/Disagree	Strongly agree	Strongly agree	Don't know	Tha last one - yellow hexagon thing
9	Strongly agree	Strongly agree	Agree	Strongly agree	No problems
10	Agree	Disagree	Strongly agree	Agree	No problems
11	Agree	Agree	Strongly agree	Disagree	The final activity
12	Strongly disagree	Strongly agree	Agree	Agree	Undoing cuts/extrudes
13	Strongly agree	Agree	Agree	Disagree	No problems
14	Strongly agree	Strongly agree	Agree	Disagree	No problems
15	Agree	Strongly agree	Agree	Agree	No problems
16	Don't know	Agree	Strongly agree	Disagree	Deciding what scale I was working at. Deciding if there was a background/ground plane.
17	Strongly agree	Agree	Strongly agree	Agree	Extrude cut shallower
18	Agree	Agree	Agree	Disagree	Hexagonal plate
19	Agree	Disagree	Strongly agree	Disagree	No problems
20	Strongly agree	Strongly agree	Strongly agree	Strongly disagree	The final shape to create with the cup and ball made me think several times about how to make a ball.
21	Agree	Agree	Strongly agree	Don't know	Making the plate - the more xomplex shapes were difficult to come up with a solution for

Participant number	Did you imagine the objects shown as 3D objects suspended in air in front of you?	Were you tempted to use gestures you use to interact with your phone or tablet?	Did the shape of the object influence the gestures you made?	Had the phone been a rectangular box, would you interact with it the same way?	Did you struggle with any actvities and if so which?
22	Agree	Disagree	Stringly agree	Don't know	It was a bit difficult to know how to spin the "ball"
23	Strongly agree	Strongly agree	Agree	Disagree	The colour changing top
24	Strongly agree	Strongly agree	Strongly agree	Disagree	The one that went from grey to yellow on top.
25	Strongly disagree	Agree	Agree	Strongly disagree	No problems
26	Strongly agree	Strongly agree	Strongly agree	Disagree	Fileting edges I think is tricky to do with gestures.
27	Strongly agree	Don't know	Agree	Agree	No problems
28	Strongly agree	Strongly agree	Agree	Don’t know	Creating objects on multiple planes i.e. hexagon shaped object
29	Agree	Disagree	Strongly agree	Disagree	No problems
30	Agree	Agree	Strongly agree	Disagree	I didn't know what the gold surface means (appearing and dissapearing)
31	Strongly agree	Strongly agree	Strongly agree	Don’t know	More complex - creating two separate shapes e.g. cup with spherical handle
32	Agree	Agree	Agree	Disagree	No problems
33	Disagree	Agree	Agree	Strongly agree	No problems
34	Strongly agree	Agree	Disagree	Strongly agree	No problems
35	Agree	Agree	Don’t know	Strongly agree	Yes - making the flaired hexagon shape
36	Strongly agree	Agree	Agree	Agree	Kept thinking about Solidworks functions/tools

Participant number	Did you imagine the objects shown as 3D objects suspended in air in front of you?	Were you tempted to use gestures you use to interact with your phone or tablet?	Did the shape of the object influence the gestures you made?	Had the phone been a rectangular box, would you interact with it the same way?	Did you struggle with any actvities and if so which?
					which interferred with natural gestures
37	Strongly agree	Strongl y agree	Agree	Agree	Presentation
38	Agree	Agree	Don't know	Strongl y agree	Selection/Deselecti on Animation
39	Agree	Agree	Strongl y agree	Don't know	No problems
40	Agree	Strongl y agree	Strongl y agree	Strongl y agree	Yes the final bowl - my CAD experience hindered my imagination, but when I overcame this limitation it was much simpler.
41	Agree	Agree	Don’t know	Strongl y agree	Not really, just felt a bit weird
42	Agree	Agree	Don’t know	Agree	To a small extent the final actvitiy, only as it was a bit challening to use my imagination
43	Strongly agree	Agree	Strongl y agree	Agree	Copy pasting, selecting and deselecting a specific face
44	Agree	Agree	Disagre e	Agree	I was concerned that my gestures weren't consistent with different objects completing the same motion. Changing the colour of the surface to orange was a confusing gesture.

G 2 List of sequences in the study Part 1 in each of the videos

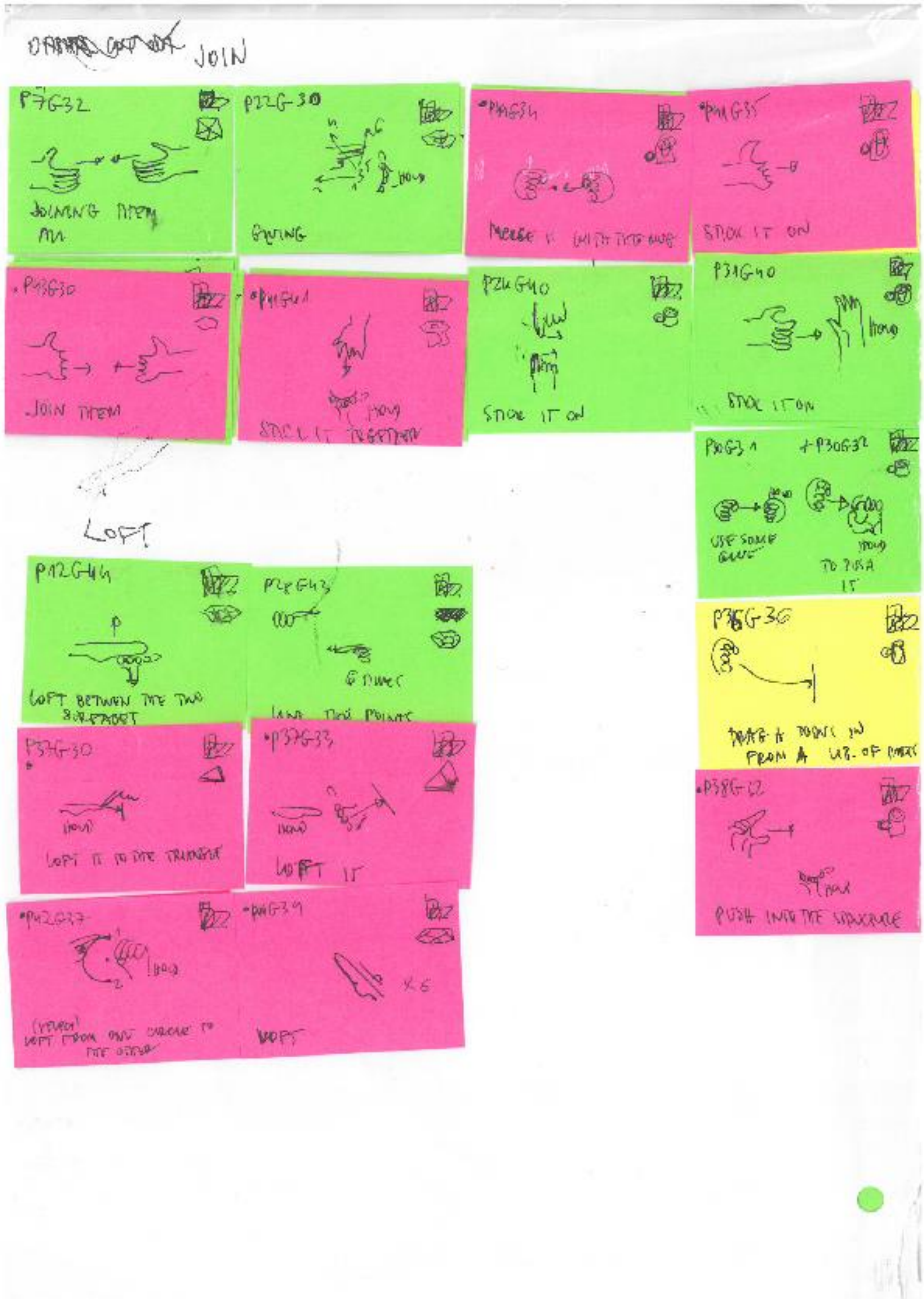
Table 22 : List of sequences in the Study part 1 in videos 1-5

Video 1	Video 2	Video 3	Video 4	Video 5
Wavy sphere rotation cw	Surface deselect	Extrude down	Phone rotation cw	Extrude down
Phone translate right	Phone translate right	Surface deselect	Chair zoom	Wavy sphere zoom out
Phone translate left	Phone translate left	Wavy sphere translate down	Extrude up	Wavy sphere translate up
Phone translate down	Wavy sphere zoom in	Wavy sphere translate right	Phone zoom in	Wavy sphere translate right
Phone zoom out	Surface select	Wavy sphere rotation ccw	Phone translate down	Wavy sphere rotation cw
Extrude cut	Extrude cut	Phone translate right	Surface deselect	Phone rotation cw
Surface deselect	Wavy sphere translate down	Extrude cut shallower	Chair rotation	Phone translate up
Surface select	Chair translation	Phone translate up	Chair translation	Surface select
Phone translate up	Chair rotation	Extrude up	Wavy sphere translate down	Wavy sphere translate down
Wavy sphere zoom out	Chair zoom	Wavy sphere zoom out	Wavy sphere translate up	Wavy sphere translate left
Phone rotation ccw	Phone translate down	Phone rotation ccw	Wavy sphere rotation cw	Phone rotation ccw
Wavy sphere zoom in	Wavy sphere rotation ccw	Extrude cut	Extrude cut	Extrude cut
Wavy sphere translate left	Extrude down	Surface select	Phone translate left	Extrude up
Phone zoom in	Extrude cut shallower	Wavy sphere translate up	Wavy sphere rotation ccw	Chair translation
Extrude down	Wavy sphere zoom out	Wavy sphere zoom in	Phone rotation ccw	Chair rotation
Phone rotation cw	Extrude up	Chair zoom	Extrude down	Chair zoom
Wavy sphere translate right	Wavy sphere translate up	Chair rotation	Wavy sphere zoom in	Phone zoom in
Extrude up	Phone rotation ccw	Chair translation	Wavy sphere translate right	Surface deselect
Wavy sphere translate up	Phone zoom out	Wavy sphere translate left	Wavy sphere translate left	Wavy sphere zoom in
Wavy sphere rotation ccw	Phone zoom in	Wavy sphere rotation cw	Surface select	Phone translate down
Wavy sphere translate down	Phone translate up	Phone translate down	Phone zoom out	Phone translate left
Extrude cut shallower	Phone rotation cw	Phone rotation cw	Wavy sphere zoom out	Phone translate right
Chair rotation	Wavy sphere translate right	Phone zoom in	Phone translate up	Wavy sphere rotation ccw
Chair translation	Wavy sphere translate left	Phone zoom out	Extrude cut shallower	Extrude cut shallower
Chair zoom	Wavy sphere rotation cw	Phone translate left	Phone translate right	Phone zoom out

Table 23 : List of sequences in the Study part 1 in videos 6-10

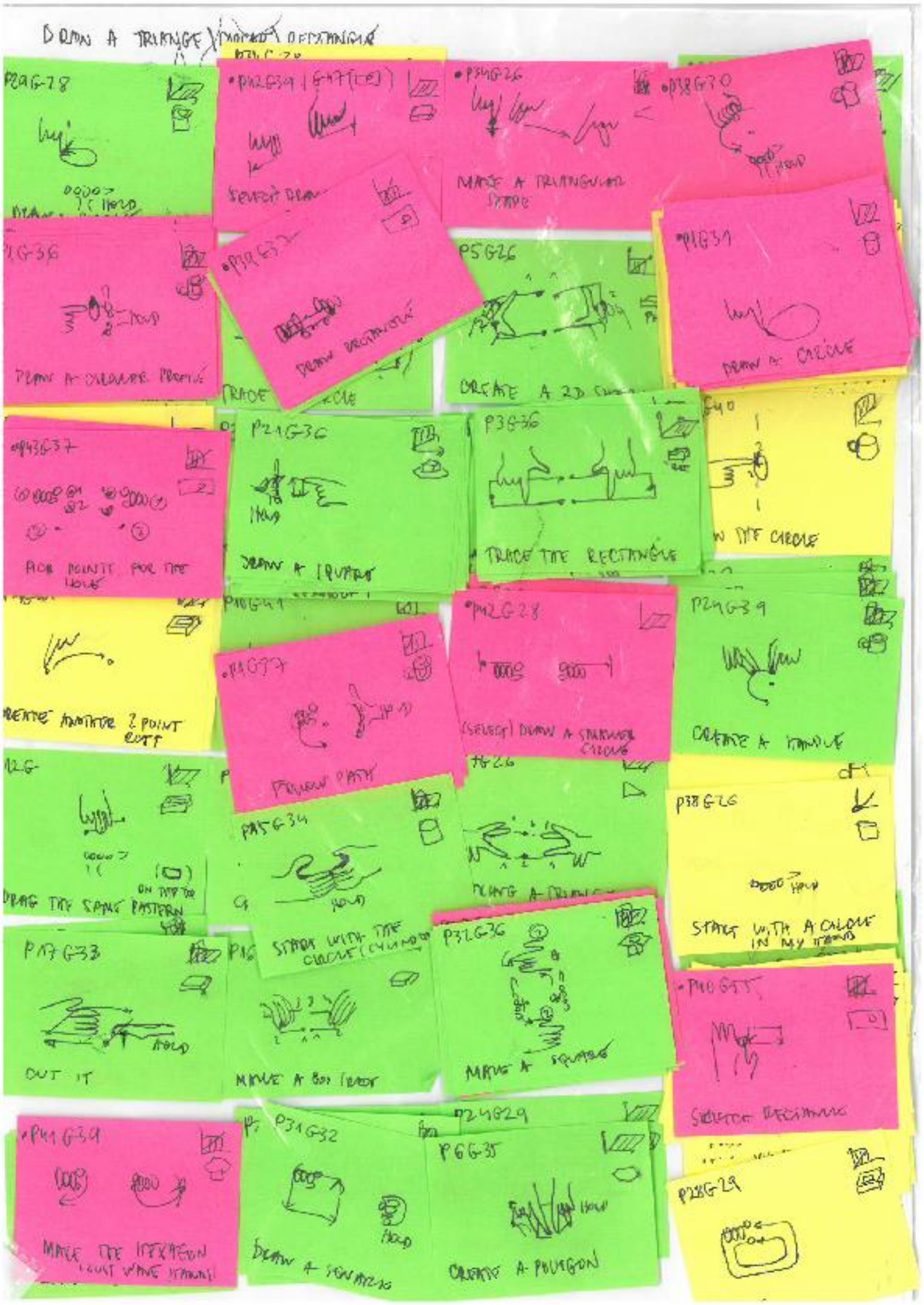
Video 6	Video 7	Video 8	Video 9	Video 10
Wavy sphere rotation ccw	Wavy sphere translate up	Chair translation	Extrude cut shallower	Phone rotation ccw
Extrude up	Extrude cut	Phone translate right	Extrude up	Phone zoom in
Extrude cut shallower	Phone rotation cw	Phone translate down	Surface deselect	Chair zoom
Phone translate left	Wavy sphere zoom out	Phone zoom in	Phone rotation ccw	Chair translation
Wavy sphere rotation cw	Surface select	Phone zoom out	Wavy sphere translate left	Phone translate up
Wavy sphere translate right	Wavy sphere rotation ccw	Phone rotation ccw	Phone zoom out	Phone zoom out
Phone zoom in	Phone translate down	Wavy sphere rotation ccw	Wavy sphere rotation ccw	Wavy sphere translate left
Extrude down	Wavy sphere zoom in	Wavy sphere translate down	Phone translate down	Wavy sphere translate up
Wavy sphere zoom in	Surface deselect	Wavy sphere zoom in	Wavy sphere zoom out	Wavy sphere translate down
Phone zoom out	Phone translate up	Wavy sphere translate up	Phone translate left	Phone translate left
Wavy sphere translate up	Extrude up	Phone rotation cw	Wavy sphere zoom in	Phone translate right
Extrude cut	Extrude down	Phone translate left	Phone zoom in	Phone rotation cw
Wavy sphere translate left	Wavy sphere translate right	Extrude cut shallower	Extrude cut	Wavy sphere rotation cw
Chair zoom	Chair zoom	Chair zoom	Surface select	Extrude cut
Wavy sphere translate down	Chair rotation	Wavy sphere translate right	Wavy sphere rotation cw	Wavy sphere zoom out
Phone rotation cw	Chair translation	Extrude down	Extrude down	Extrude cut shallower
Surface select	Wavy sphere translate down	Surface select	Phone translate right	Surface select
Phone translate down	Wavy sphere translate left	Extrude cut	Chair translation	Phone translate down
Surface deselect	Phone translate right	Phone translate up	Chair zoom	Wavy sphere translate right
Wavy sphere zoom out	Phone zoom out	Extrude up	Chair rotation	Extrude down
Chair translation	Phone rotation ccw	Wavy sphere rotation cw	Wavy sphere translate right	Wavy sphere rotation ccw
Chair rotation	Wavy sphere rotation cw	Surface deselect	Wavy sphere translate up	Wavy sphere zoom in
Phone translate right	Phone translate left	Wavy sphere translate left	Phone translate up	Extrude up
Phone translate up	Extrude cut shallower	Chair rotation	Phone rotation cw	Surface deselect
Phone rotation ccw	Phone zoom in	Wavy sphere zoom out	Wavy sphere translate down	Chair rotation

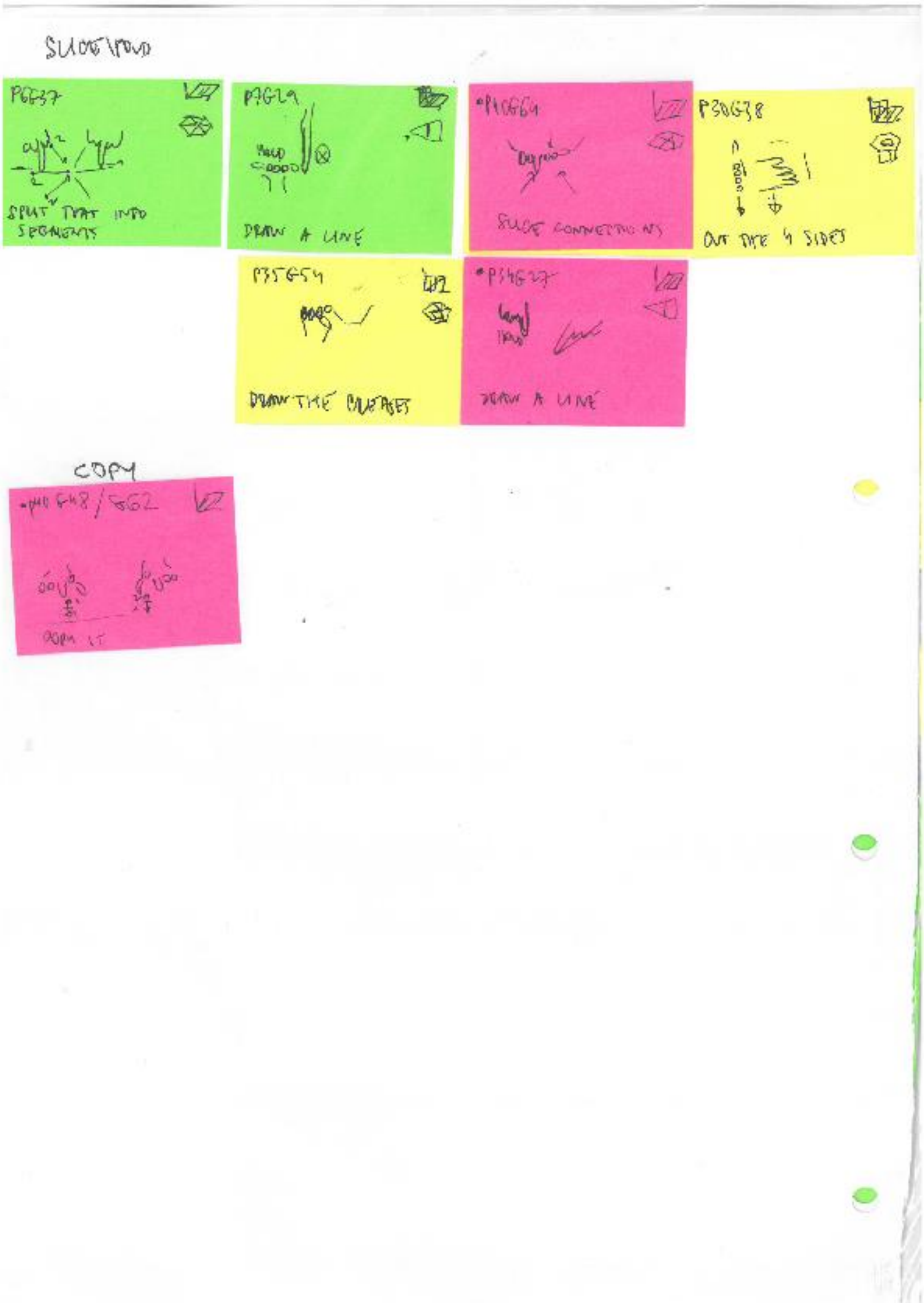
G 3 Sketches of gestures performed in the Full study (Part 1 and Part 2)


JOIN
P7G32
JOINING THEM
P22G30
GLUING
STICK IT ON
P27G40
STICK IT ON
P31G40
STICK IT ON
JOIN THEM
LOFT
P12G44
LOFT BETWEEN THE TWO SURFACES
P35G36
P38G42
PUSH INTO THE STRUCTURE
P37G33
LOFT IT
x6
LOFT


SET THE BASE / CREATE A PLANE / SELECT THE PLANE
P5G37
SELECT (PLANE)
ADD A PERPENDICULAR PLANE
P2G30
HOLD
P5G49
SELECT A PLANE
P2G40
SELECT THE PLANE (BY DIRECTION)
P28G39
NEW PLANE
P32G26
MOVE A PLANE
FLATTEN IT
P37G28
GET A PLANE
START A NEW MOTIF
SELECT PLANE
PROJECT THE PLANE
PROJECT A PLANE
P40G26/G46/G54
SNAP FINGER TO INDICATE SWITCHING

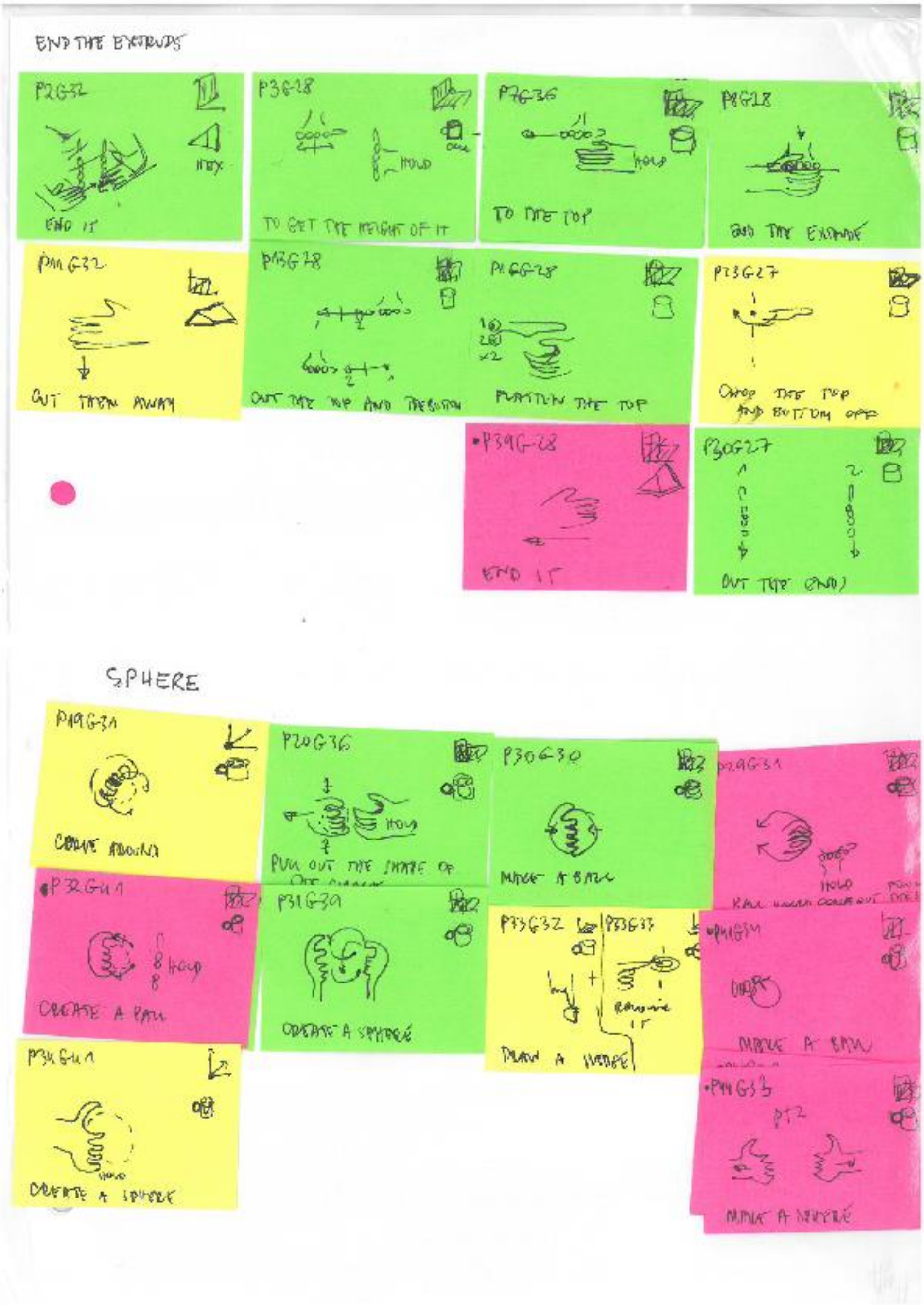

ROTATE CW / CCW
ROTATE
ROTATE
ROTATE ON 2 POINTS
ROTATE
ROTATE
TURN IT AROUND
ROTATE (SPIN IT AROUND)
ROTATE
SPIN IT
ROTATE
ROTATE
ROTATE
TURN IT AROUND
PAN
LIFT IT
PLACE IT DOWN


MAKE A TRIANGULAR SHAPE
DRAW A CIRCLE
TRACE THE RECTANGLE
CREATE A HANDLE
START WITH A CIRCLE IN MY HAND
MAKE A SQUARE
CREATE A POLYGON

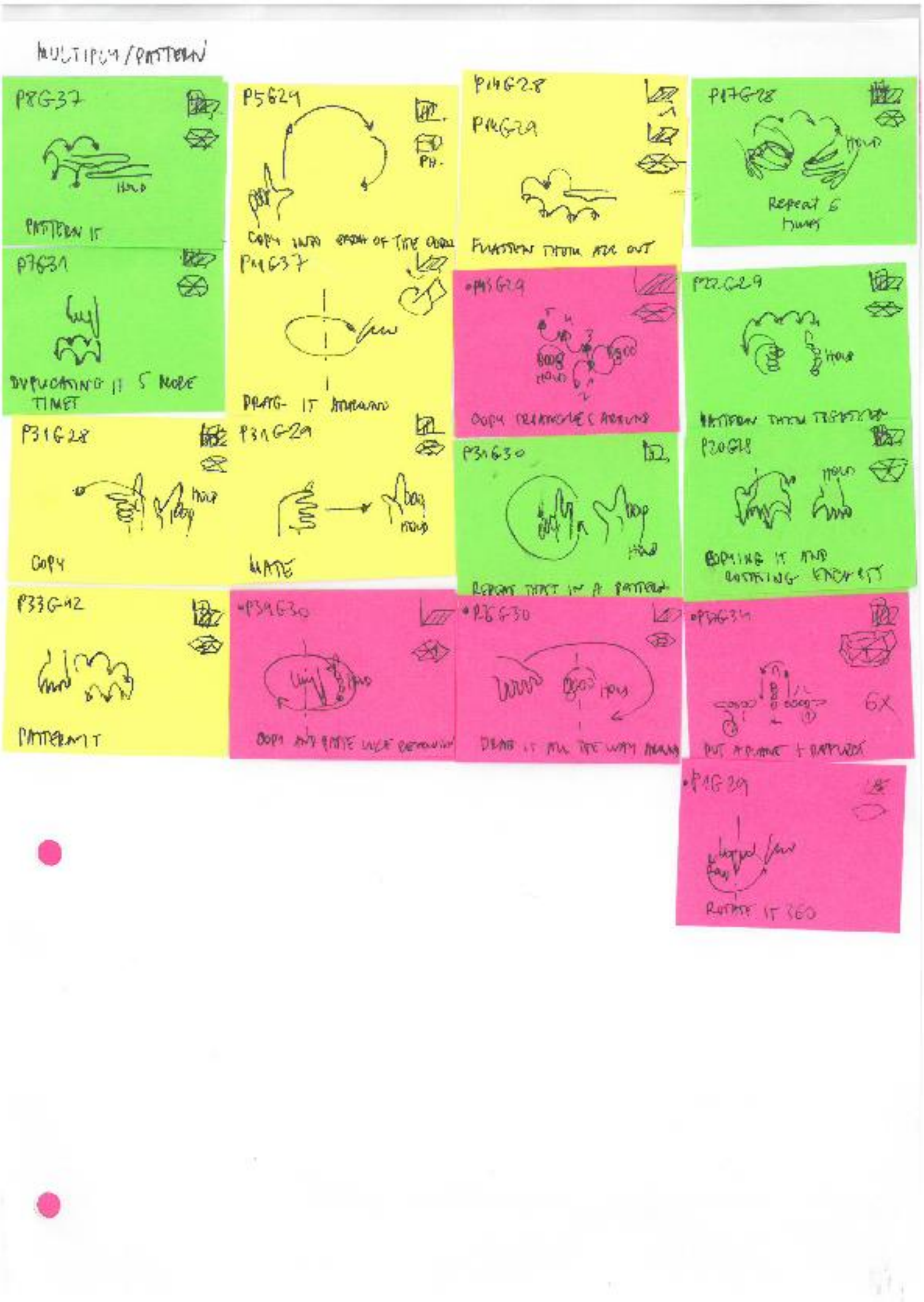

SLICE\FOLD
SPLIT THAT INTO SEGMENTS
DRAW A LINE
SLICE CONNECTIONS
CUT THE 4 SIDES
DRAW THE CREASES
DRAW A LINE
COPY
FORM IT

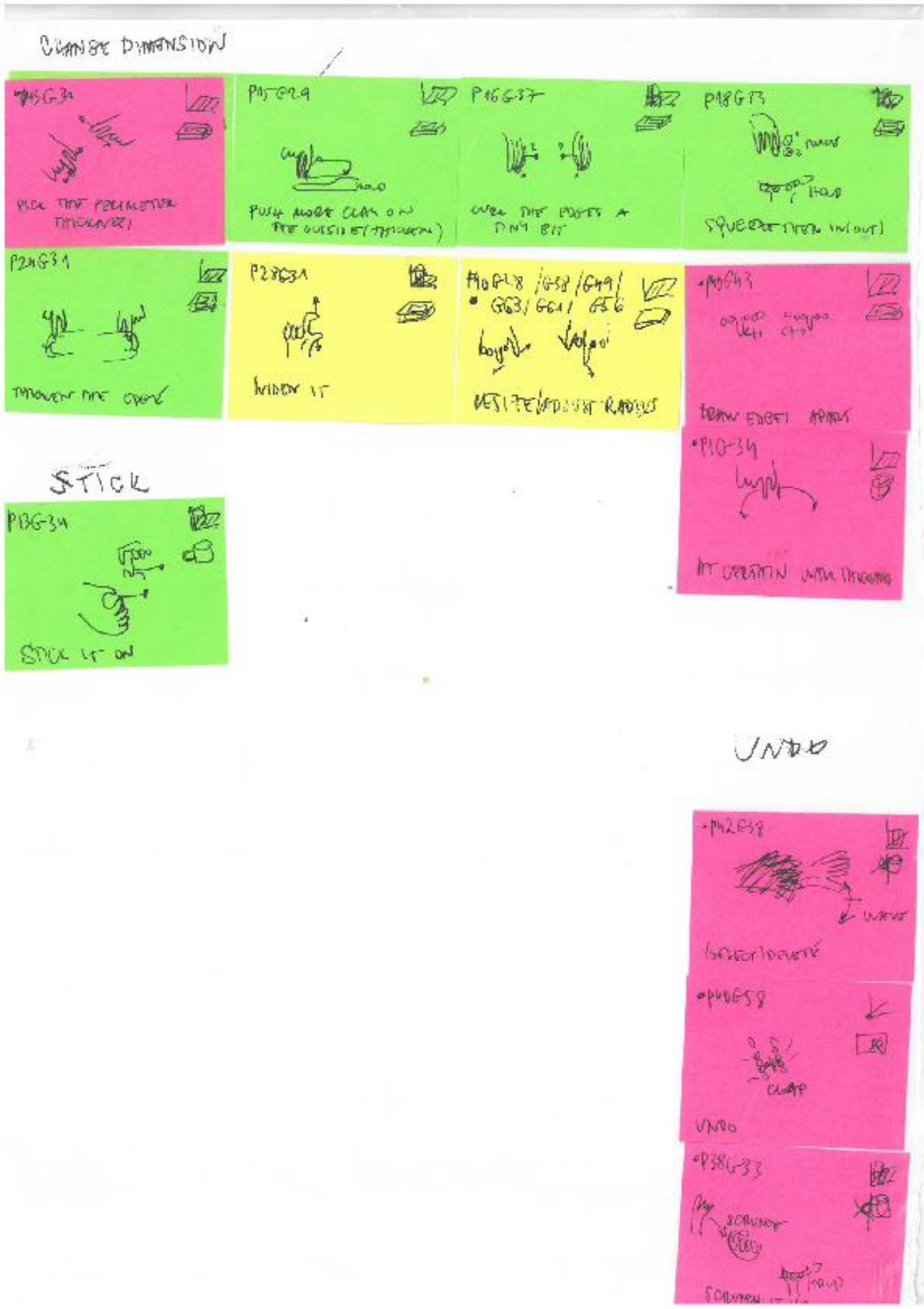

EXTRUDE
P21G37
PULL IT OUT (EXTRUDE)
P3G37
PULL THAT UPWARDS
P6G27
EXTRUDE UP
EXTRUDE DOWN
EXTRUDE IT
P6G36
P16G38
P11G40
EXTRUDE IT UP
PULL UP THE EDGES
RAISE IT
P28G38
P29G35
PULL EACH SIDE OUT
EXTRUDE IT
P31G36
P31G33
PULL IT BACK
P29G37
EXTRUDE DOWN
EXTRUDE IT UP
P36G27
DRIVE IT UPWARDS

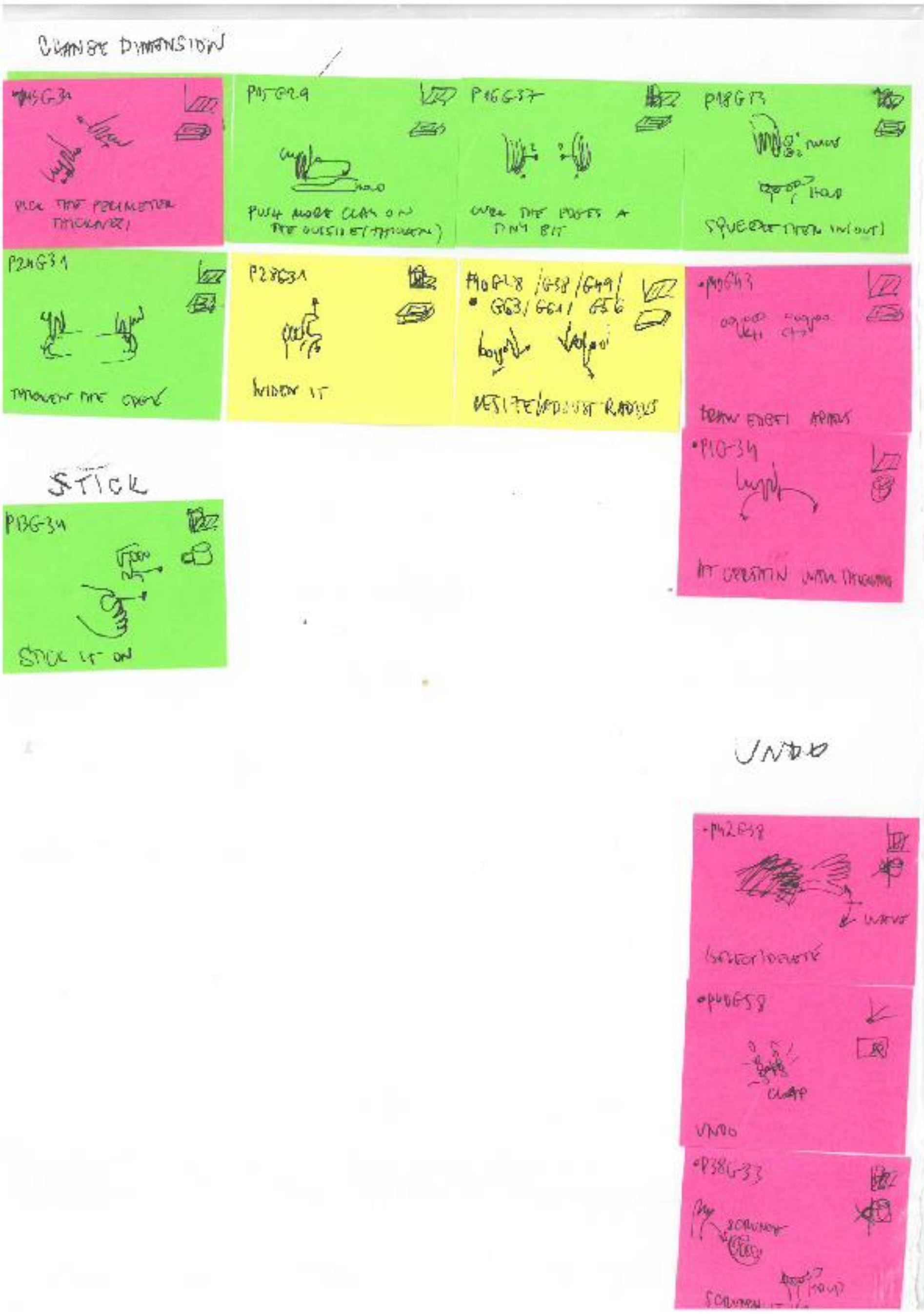

EXTRUDE OUT
P42G29
DRAG DOWN TO OUT
EXTRUDE IT DOWN
P35G37
P32G40
MAKE A HOLE INSIDE
P2G37
P19G38
PUSH IT DOWN
OUT DOWN INTO IN (EXT.OUT)
TAKE THE TOP OFF
P14G33
SCOOP IT OUT
PUSH IT DOWN (OUT OUT)
P16G40
PUSH THAT DOWN
P34G38
EXTRUDE IT (OUT)
P12G38
P15G28
P38G37
PUSH THE HOLE IN
P47G38
P17G36
CUT THE HOLE
DIG IT OUT INSIDE
EXTRUDE (OUT)
P19G29
PUSH DOWN (OUT OUT)
P24G31
DIG IT OUT
CUT OUT THE TOP
P26G40
OUT DOWN
P40G57
OUT
P28G30
P42G42
(SELECT) OUT

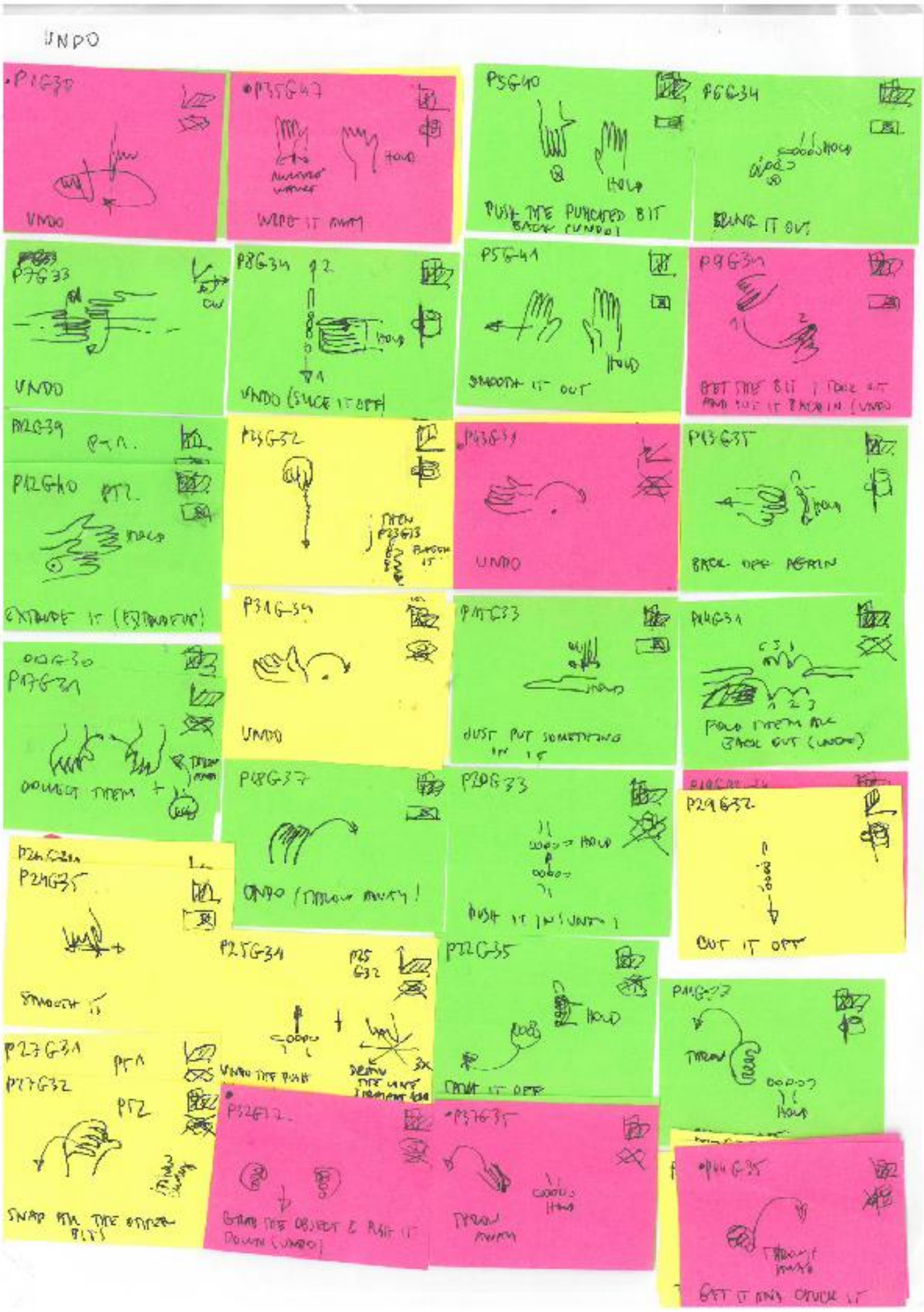


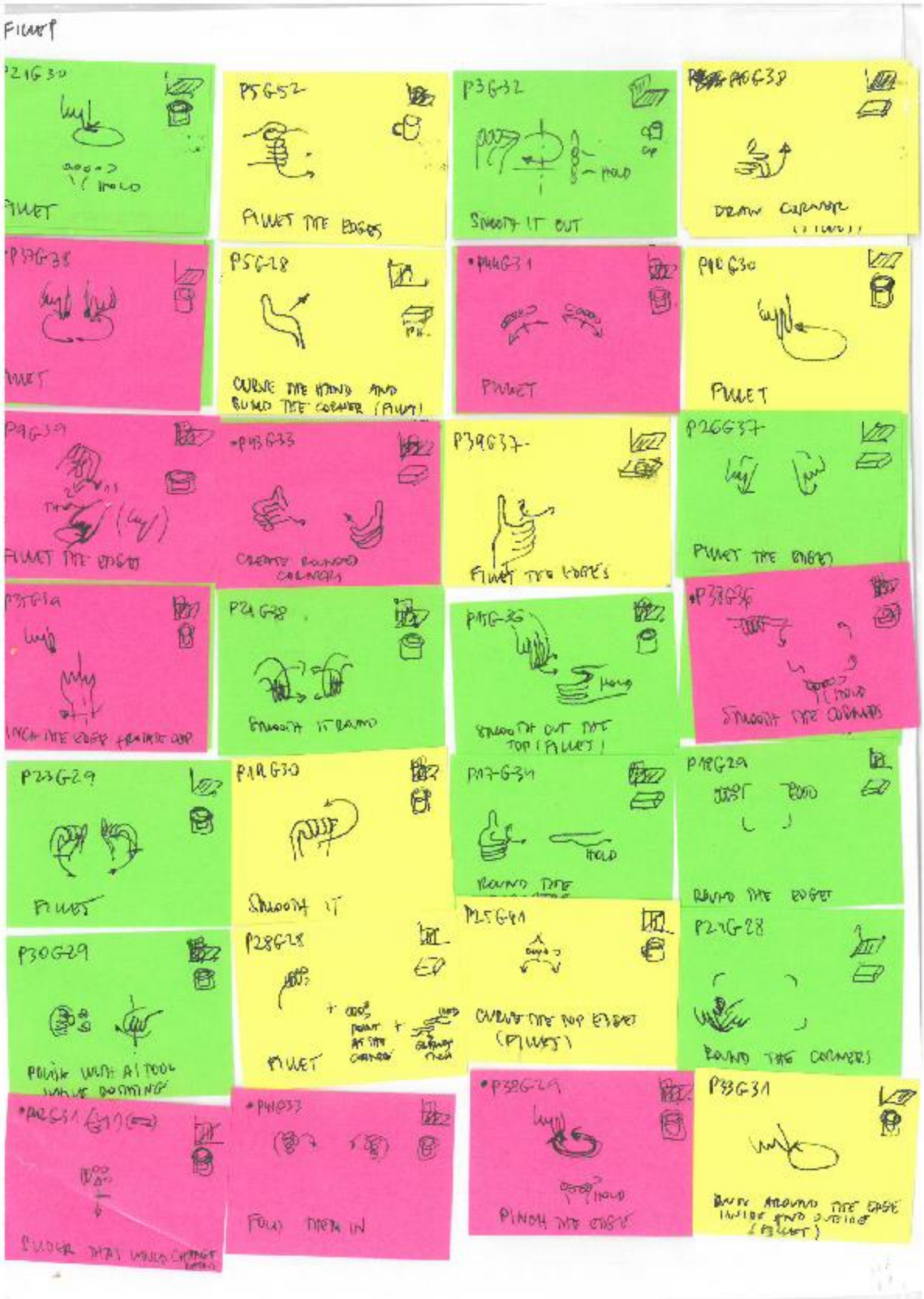

ZOOM (IN / OUT)
PULL IT TOWARDS ME (ZOOM IN)
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN
ZOOM IN


MULTIPLY / PATTERN
P8G37
PATTERN IT
P14G28
P17G28
Repeat 6 times
P7G31
DUPLICATING IT 5 MORE TIMES
P31G28
COPY
P31G29
HOLD
P31G30
P20G28
P33G42
PATTERN IT
6X
ROTATE IT 360


CHANGE DIMENSION
PICK THE PERIMETER THICKNESS
PUSH MORE CLAY ON THE OUTSIDE (THICKEN)
SQUEEZE THEM IN/OUT
THICKEN THE EDGE
WIDEN IT
STICK
STICK IT ON
DRAW EDGES APART
UNDO
WAVE
CLAP
SCRUNCH

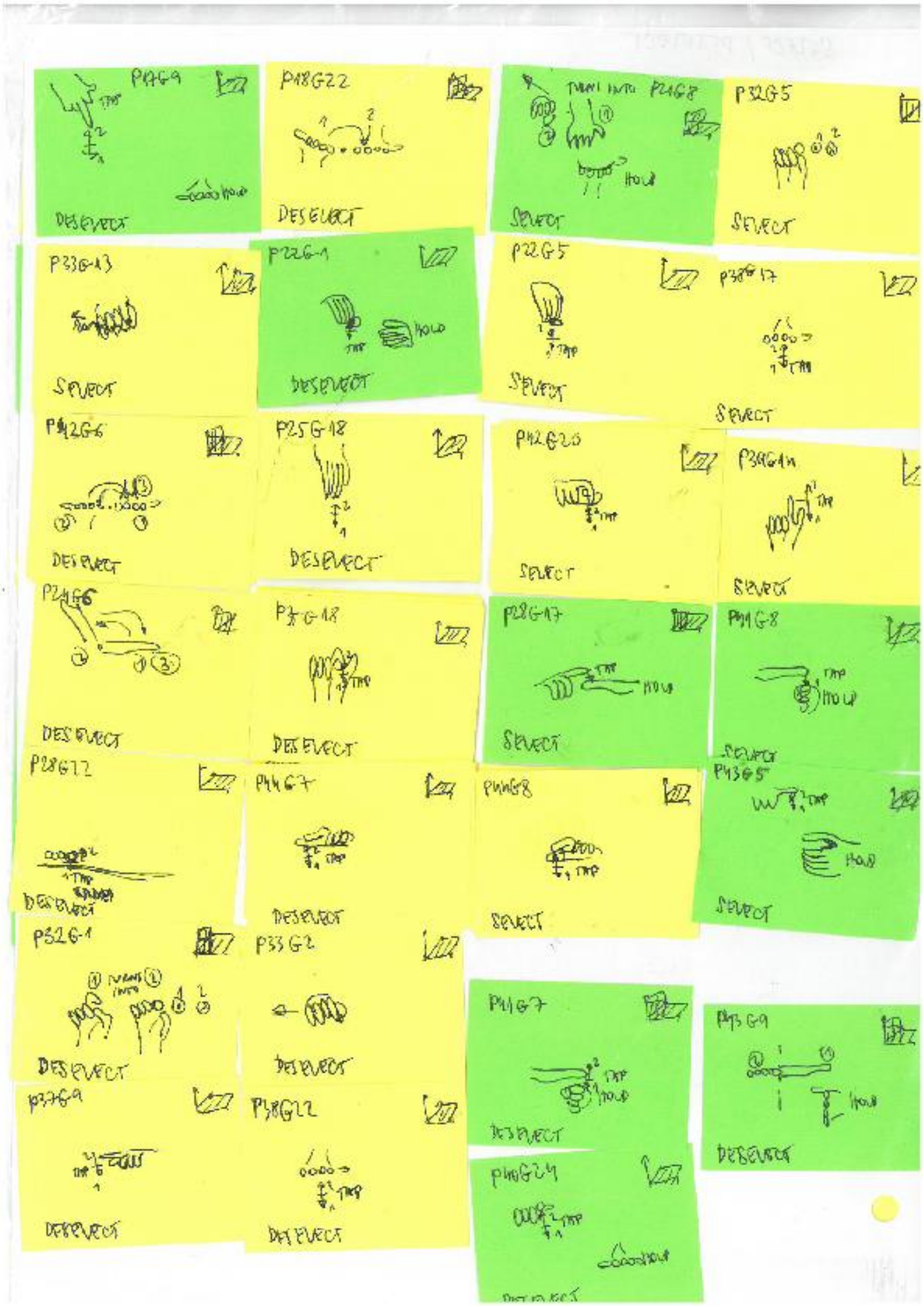

CHANGE DIMENSION
PICK THE PERIMETER THICKNESS
PUSH MORE CLAY ON THE OUTSIDE (THICKEN)
HOLD
SQUEEZE THEM IN/OUT
THICKEN THE EDGE
WIDEN IT
STICK
STICK IT ON
UNDO
WAVE
UNDO
CLAP

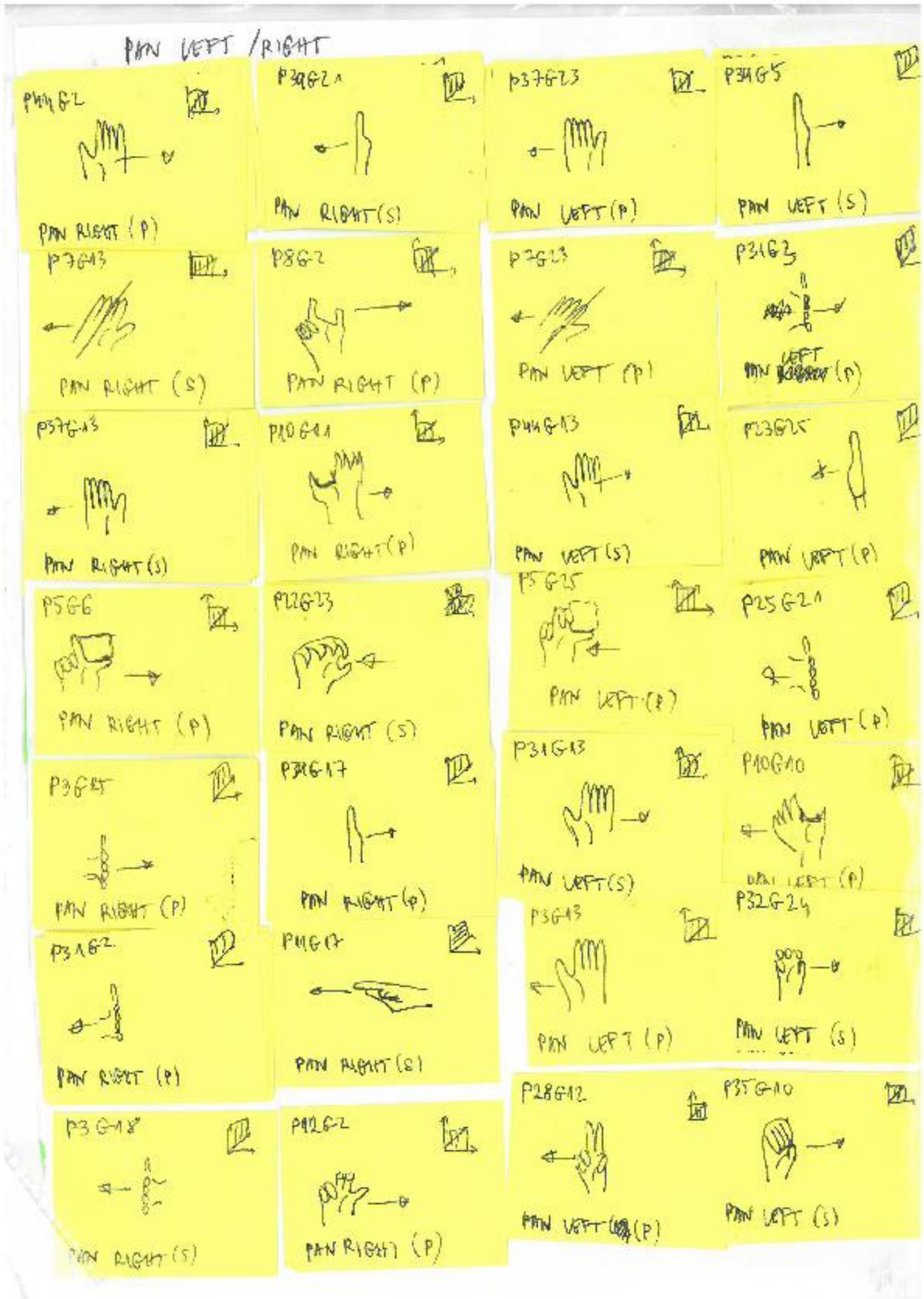





SCALE
P5G31
CROP IT DOWN
P5G45
P6G30
P12G34
SCALE
P48G31
RESIZE IT
P33G29
SCALE IT
P36G37
SIZE IT
P12G42
Blend
P27G28
BEND (FOLD IT)
P43G28
FOLD
P36G29
BEND IT
P33G49
P8G36
CREATE A FOLD
P23G36
P14G28
LIFT IT UP
P25G30
PUSH THE MIDDLE DOWN (BEND)
P3G36
FOLD THE EDGE
P32G29
P32G33
BEND IT
P35G56
PULL DOWN (BEND)
P10G65
PUSH CENTRE DOWN (BEND)
P41G40
DENT IT IN
P1G28
BEND IT


SELECT / DESELECT
DESELECT
SELECT
DESELECT
SELECT
SKIPPED
SELECT
DESELECT
SKIPPED




PAN LEFT /RIGHT
PAN RIGHT (P)
PAN RIGHT (S)
PAN LEFT (P)
PAN LEFT (S)
PAN RIGHT (S)
PAN RIGHT (P)
PAN LEFT (P)
PAN RIGHT (S)
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PAN LEFT (S)
PAN LEFT (P)
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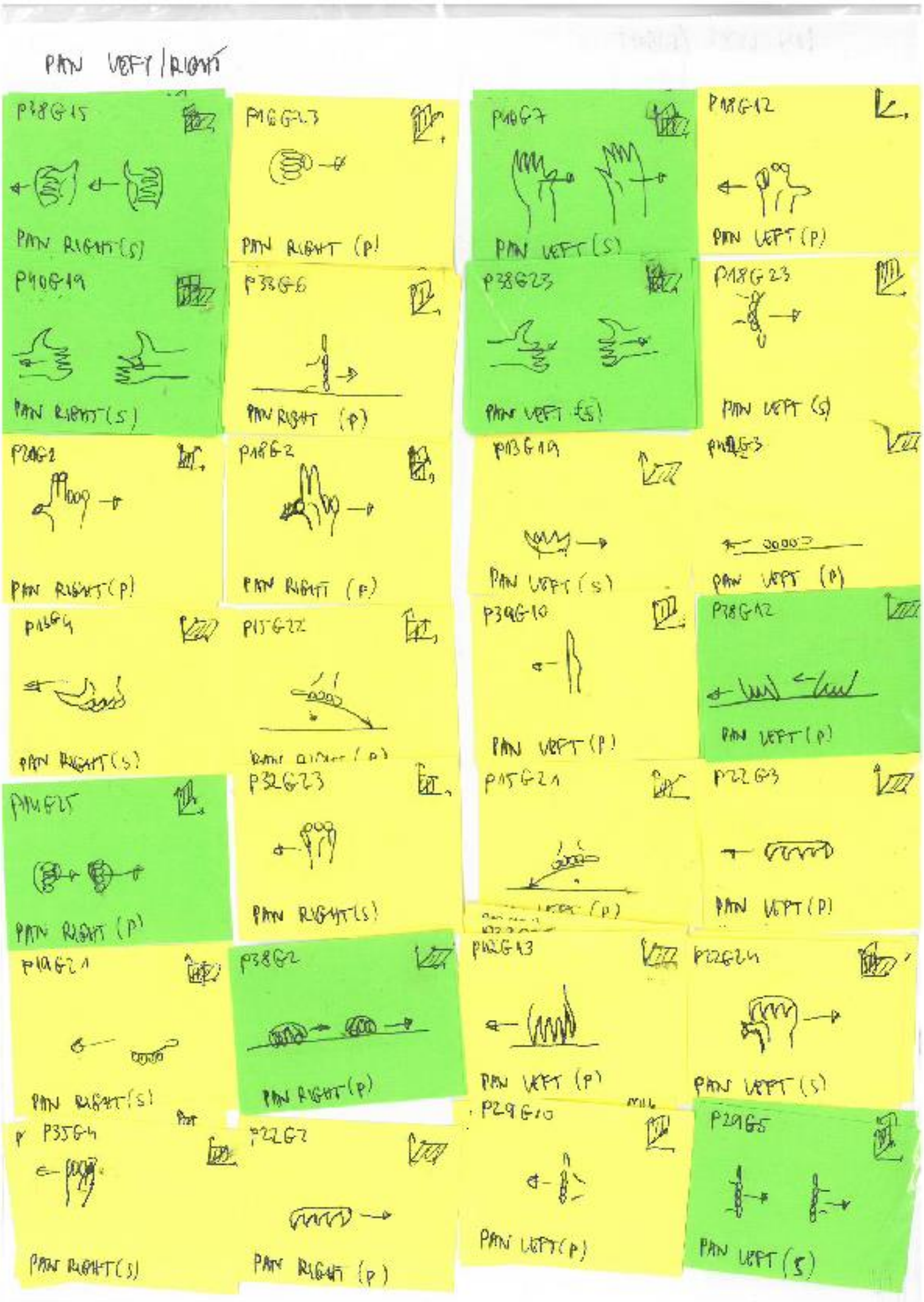
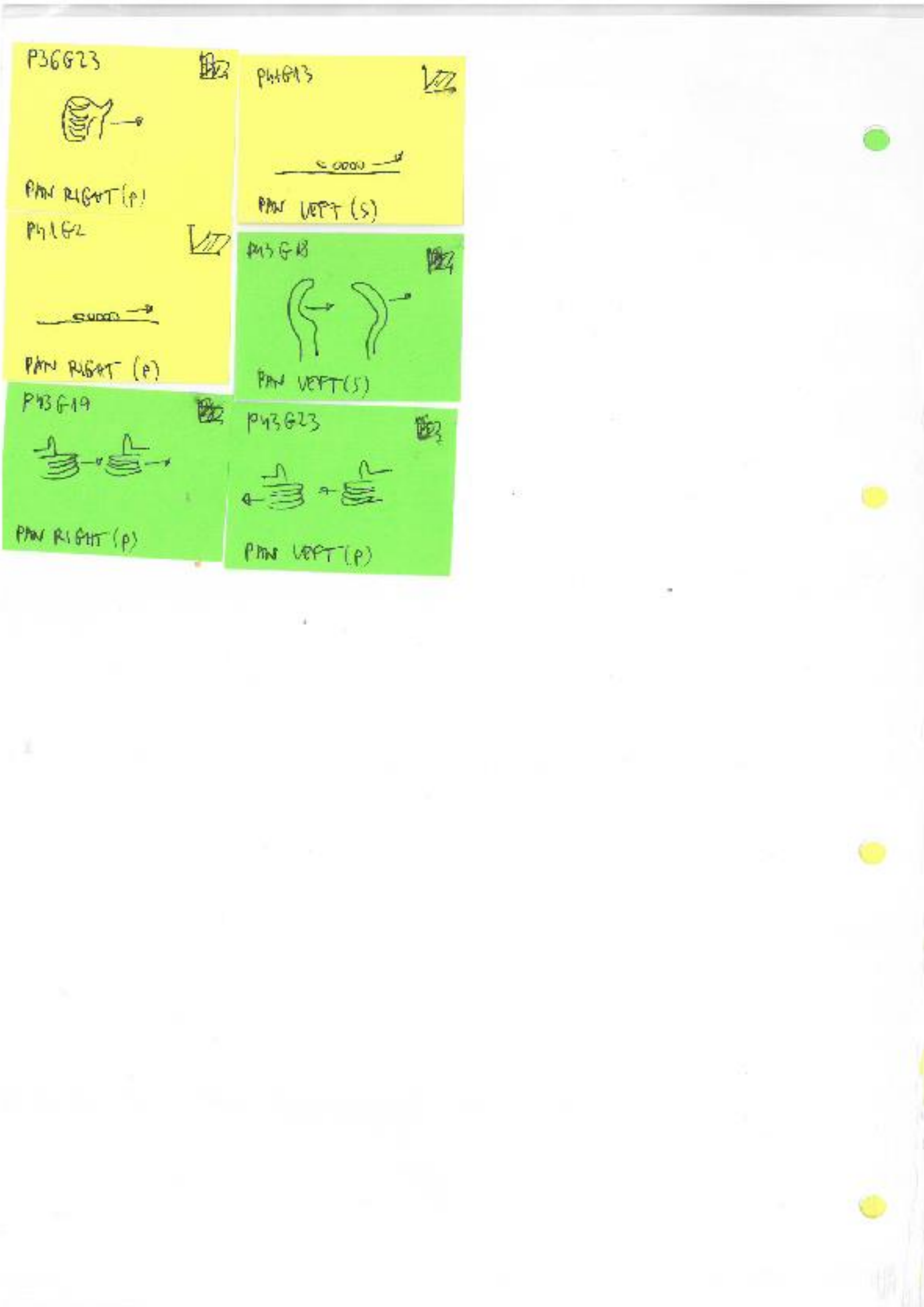
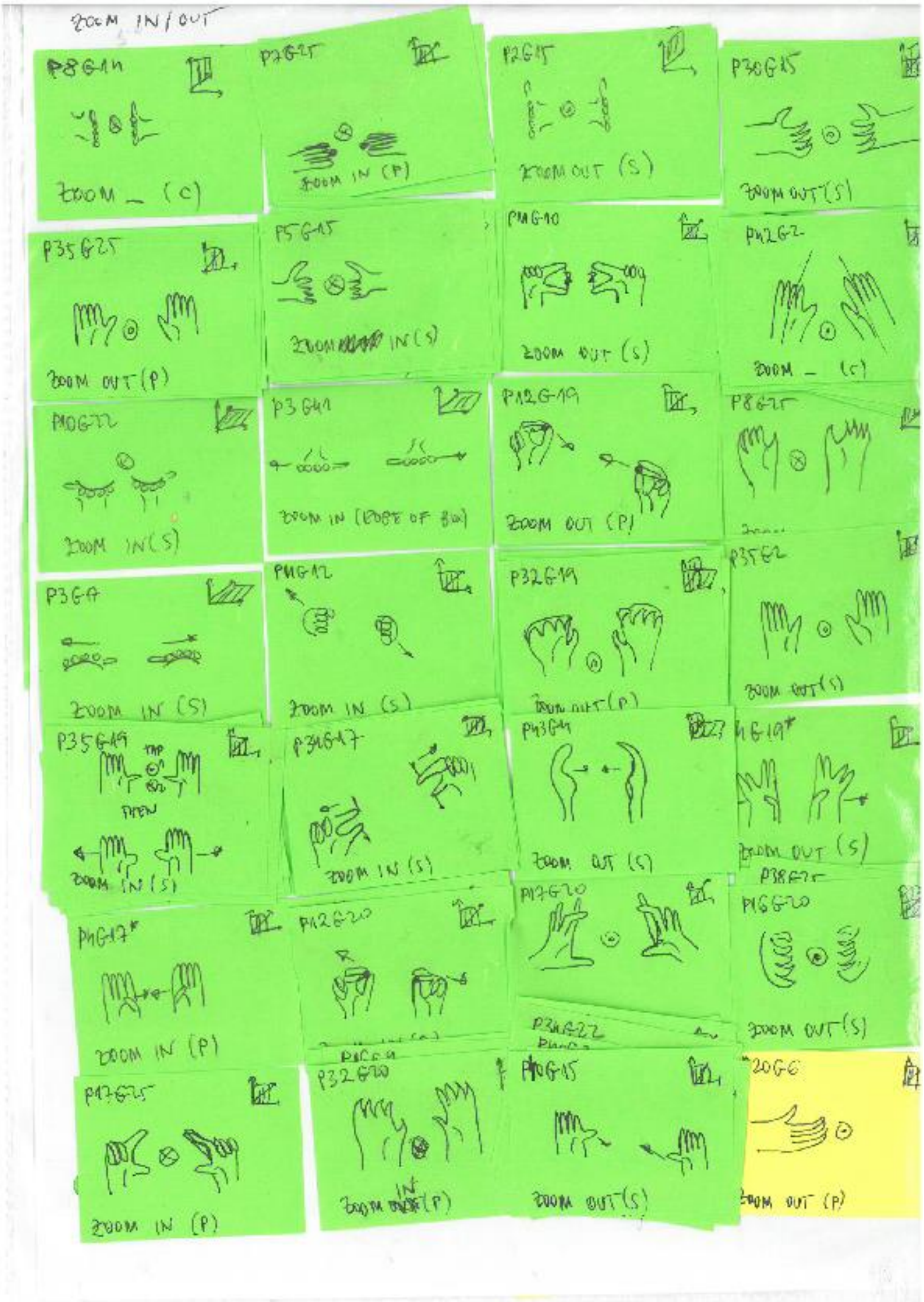
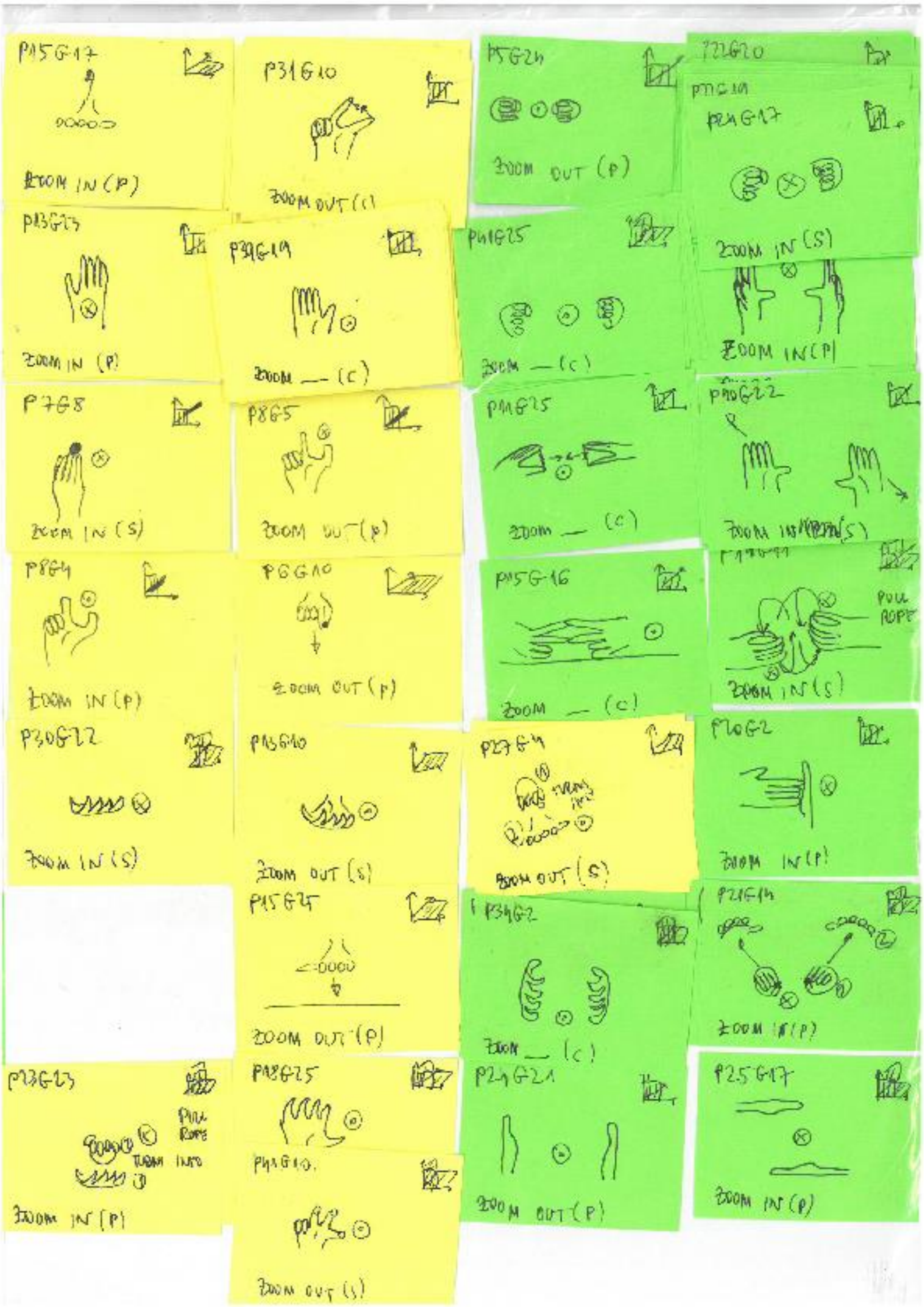
PAN RIGHT (S)
PAN LEFT (P)
PAN LEFT (S)
PAN RIGHT (S)
PAN RIGHT (P)
PAN LEFT (S)

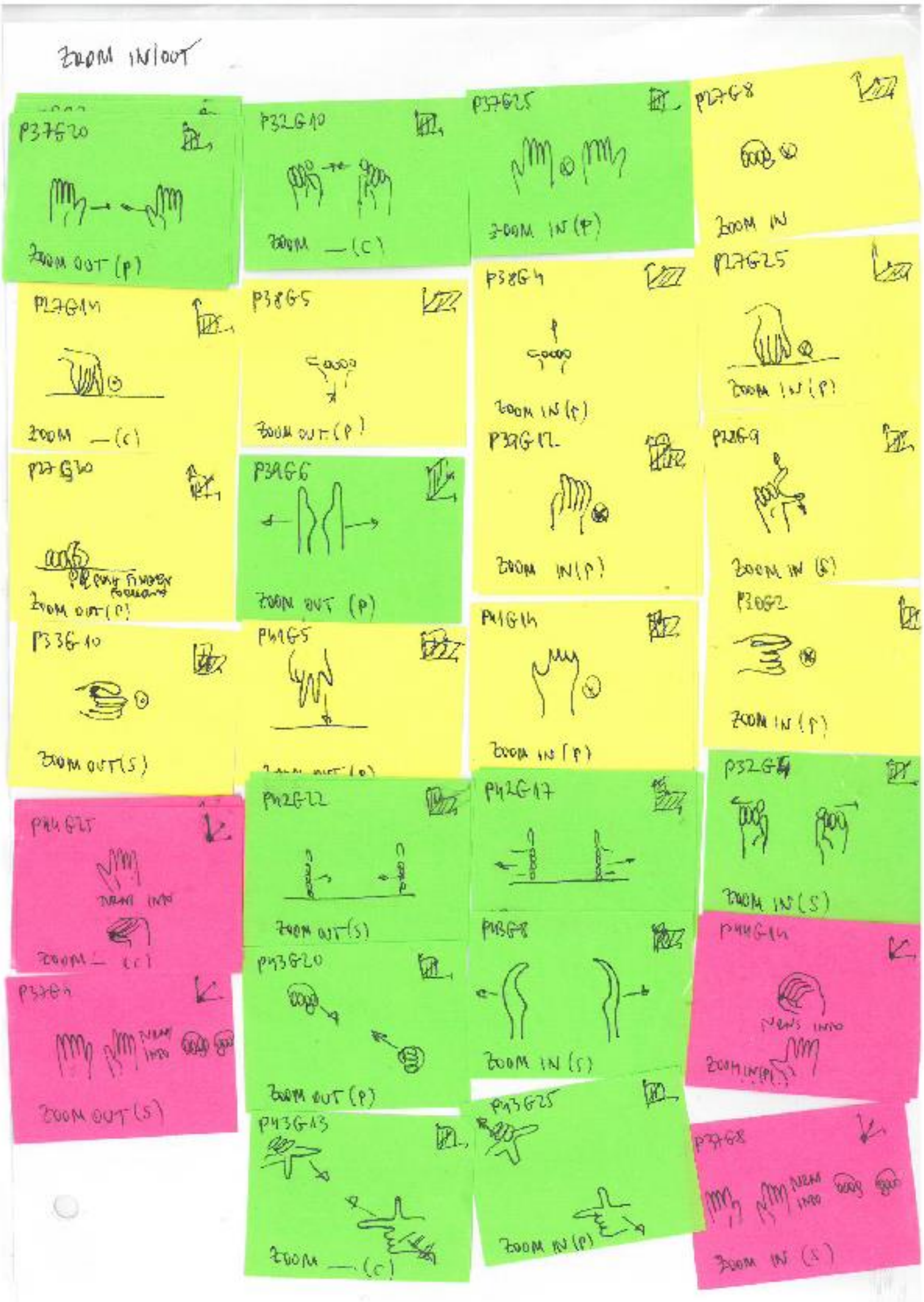

PAN LEFT/RIGHT
P38G15
PAN RIGHT (S)
P16G23
PAN RIGHT (P)
P10G7
PAN LEFT (S)
P18G12
PAN LEFT (P)
P40G19
PAN RIGHT (S)
P33G6
PAN RIGHT (P)
P38G23
PAN LEFT (S)
P18G23
PAN LEFT (S)
PAN RIGHT (P)
PAN RIGHT (P)
PAN LEFT (S)
PAN LEFT (P)
P39G10
PAN LEFT (P)
PAN LEFT (P)
PAN RIGHT (S)
P32G23
PAN RIGHT (P)
PAN RIGHT (S)
PAN LEFT (P)
P38G2
PAN RIGHT (S)
PAN RIGHT (P)
PAN LEFT (P)
PAN LEFT (S)
P35G4
P22G2
P29G10
P29G5
PAN RIGHT (S)
PAN RIGHT (P)
PAN LEFT (P)
PAN LEFT (S)


PAN LEFT / RIGHT
PAN RIGHT (P)
PAN RIGHT (S)
PAN LEFT (P)
PAN LEFT (S)
PAN RIGHT (S)
PAN RIGHT (P)
PAN LEFT (S)
PAN LEFT (S)
PAN RIGHT (P)
PAN RIGHT (P)
PAN LEFT (S)
PAN LEFT (P)
PAN RIGHT (S)
PAN RIGHT (S)
PAN LEFT (P)
PAN LEFT (S)
PAN RIGHT (S)
PAN RIGHT (S)
PAN LEFT (P)
PAN LEFT (S)
PAN RIGHT (P)
PAN RIGHT (P)
PAN LEFT (S)
PAN RIGHT (P)
PAN RIGHT (P)
PAN RIGHT (S)
PAN LEFT (P)
PAN RIGHT (S)


P36G23
PAN RIGHT (P)
P41G13
PAN LEFT (S)
P41G2
PAN RIGHT (P)
P43G18
PAN LEFT (S)
P43G19
PAN RIGHT (P)
P43G23
PAN LEFT (P)





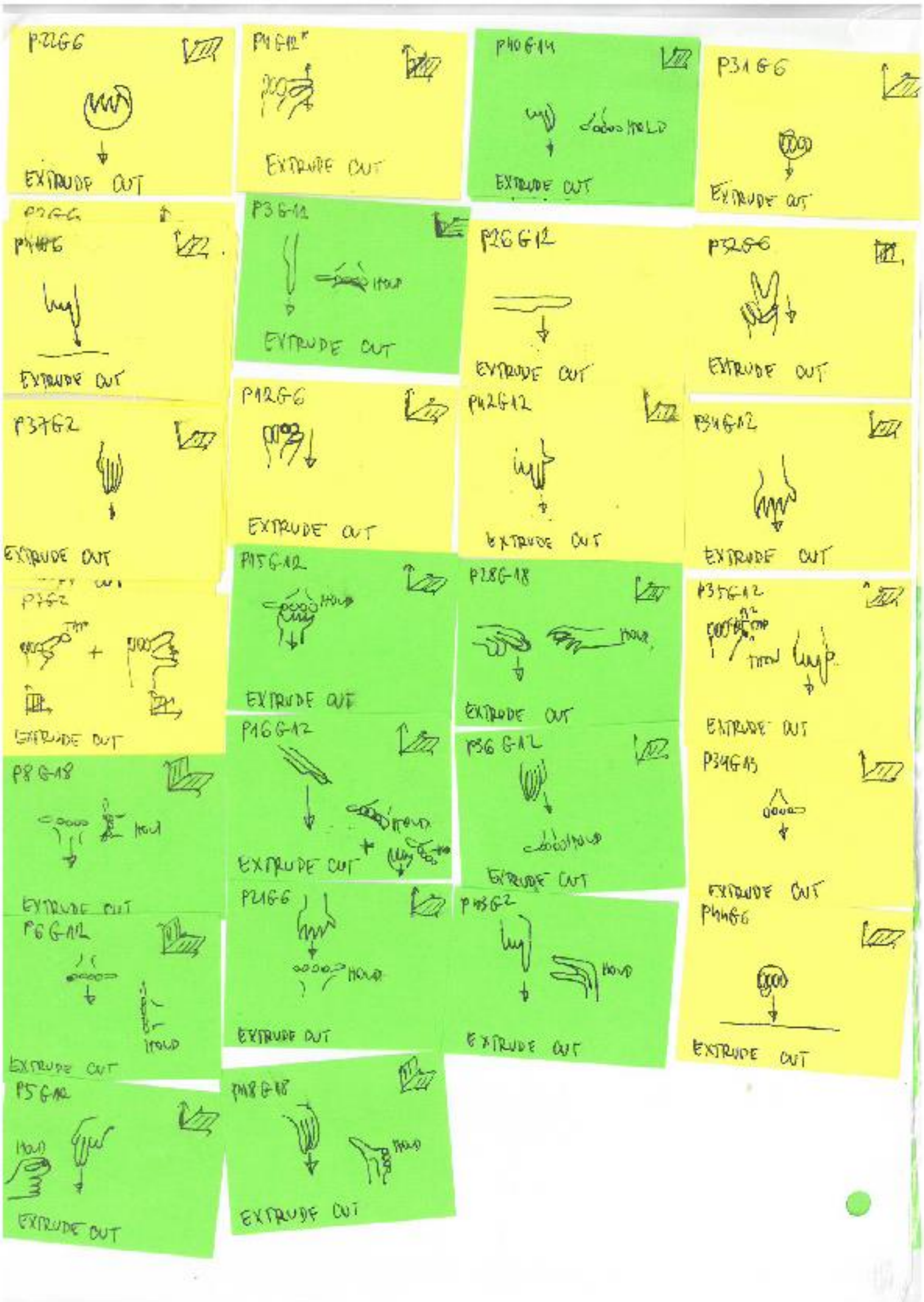

ZOOM IN/OUT
P37G20
ZOOM OUT (P)
P32G10
ZOOM — (C)
P37G25
ZOOM IN (P)
P27G8
ZOOM IN
P27G25
ZOOM IN (P)
P38G4
ZOOM IN (C)
P38G5
ZOOM OUT (P)
P27G30
P39G6
ZOOM OUT (P)
P37G12
ZOOM IN (P)
P33G10
ZOOM OUT (S)
P41G5
P41G14
ZOOM IN (P)
ZOOM IN (P)
P32G
ZOOM IN (S)
P42G22
P42G17
ZOOM OUT (S)
P43G20
ZOOM OUT (P)
ZOOM IN (S)
ZOOM OUT (S)
P43G13
ZOOM — (C)
P43G25
ZOOM IN (P)
P37G8
ZOOM IN (S)

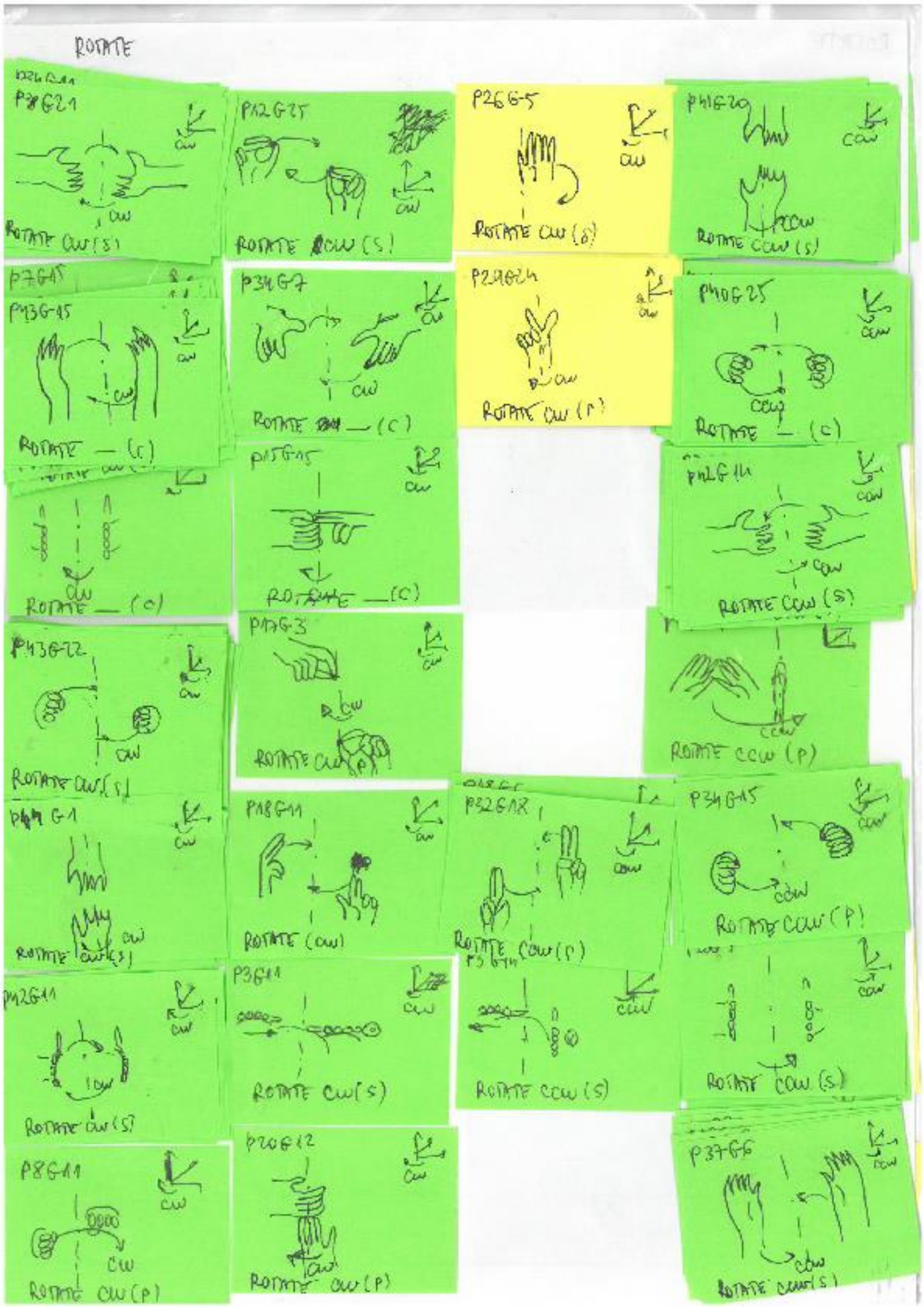

PAN UP /DOWN
PAN UP (C)
PAN DOWN (P)
PAN UP (C)
PAN DOWN (S)
PAN UP (P)
PAN DOWN (P)
LIFTING IT UPWARDS (SWIPE BEND OUTWARD) WITH TOP OF HANDS AT PIVOT POINT
PAN DOWN (S)
PAN UP (P)
PAN DOWN (S)
PAN UP (S)
PAN DOWN (S)
PAN UP (P)
PAN DOWN (S)
PAN UP (C)
PAN DOWN (P)
PAN UP (P)
PAN DOWN (S)
PAN DOWN (P)
PAN UP (C)
PAN UP (P)
PAN DOWN (S)
PAN DOWN (P)
PAN UP (C)
PAN UP (P)
PAN DOWN (P)
PAN UP (C)

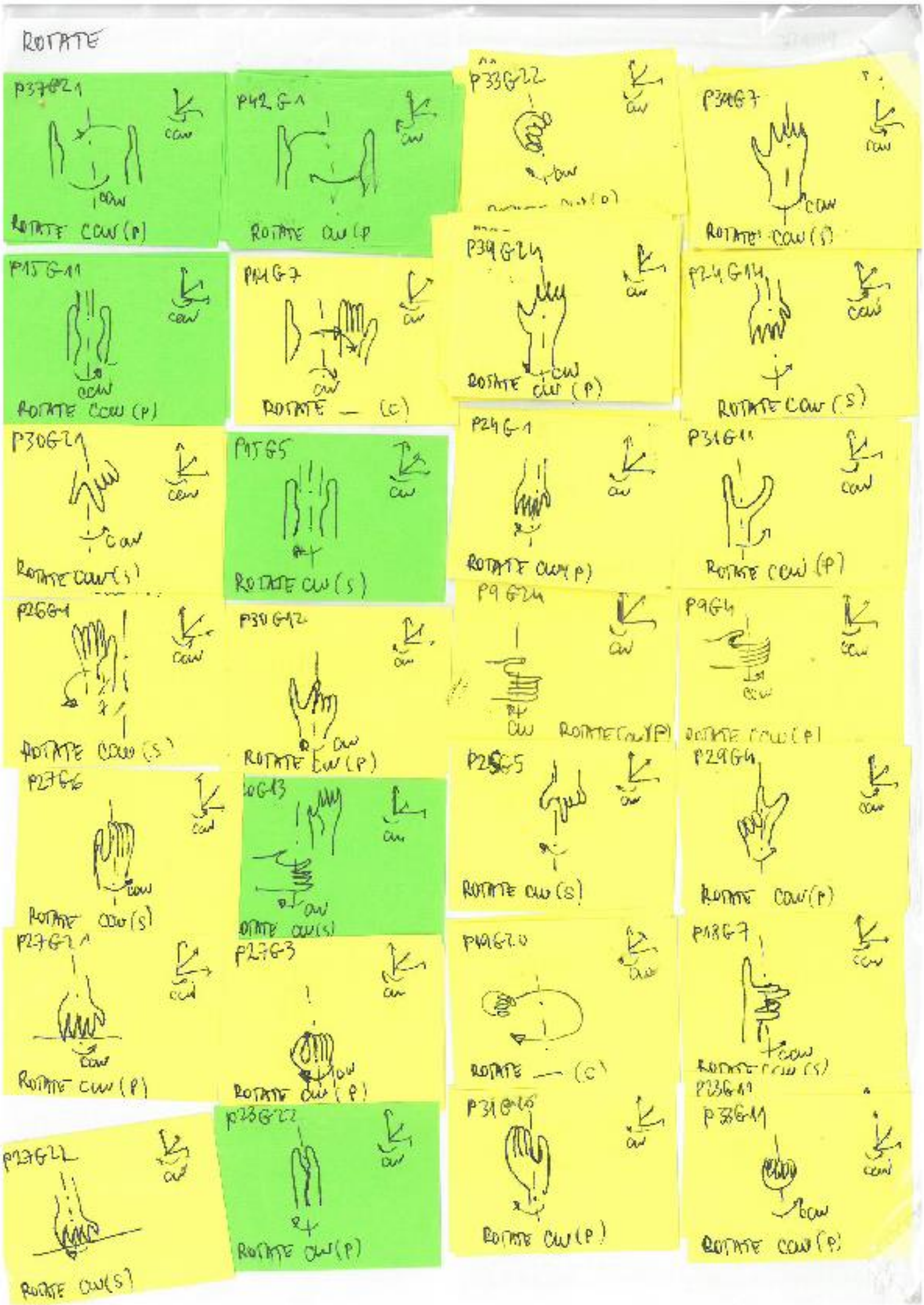

PAN UP / DOWN
P23G8
PAN UP (P)
P33G18
PAN UP (C)
P43G7
PAN DOWN (P)
P28G3
PAN DOWN (P)
P24G10
PAN UP (S)
P34G23
PAN UP (P)
P43G10
P30G9
PAN DOWN (S)
P43G16
PAN — (C)
P32G11
PAN DOWN (P)
P40G5
PAN UP (P)
P35G20
PAN DOWN (P)
P42G23
PAN UP (P)
P32G23
PAN UP (P)
P36G18
PAN DOWN (P)
P28G19
PAN UP (P)
PAN UP (P)
P39G25
PAN DOWN (S)
P30G4
PAN UP (C)
P41G19
PAN UP (S)
P43G17
PAN DOWN (S)
P30G5
PAN UP (P)
P43G1
PAN UP (S)


EXTRUDE
P33G9
EXTRUDE UP
P13G9
EXTRUDE UP
P23G9
EXTRUDE UP
EXTRUDE UP
HOLD
SIDEVIEW
EXTRUDE UP
HOLD
EXTRUDE UP
EXTRUDE UP
HOLD
EXTRUDE UP
HOLD
EXTRUDE UP
EXTRUDE UP
P28G20
HOLD
EXTRUDE UP
P36G2
EXTRUDE UP
HOLD
EXTRUDE UP
P35G13
HOLD
EXTRUDE UP
P42G3
HOLD
EXTRUDE UP
HOLD
EXTRUDE UP
EXTRUDE UP
P38G20
EXTRUDE UP
HOLD
EXTRUDE UP
EXTRUDE UP
HOLD
EXTRUDE UP


EXTRUDE








ROTATE
P28G21
CCW
ROTATE CCW(S)
P30G1
CCW
ROTATE CCW(P)
P31G7.3
CCW
ROTATE __ (C)
P42G15
CCW
ROTATE CCW (P)
P43G6
CCW
ROTATE CCW(S)
P43G21
CCW
ROTATE CCW(P)
P44G23
CCW
ROTATE __ (C)
P32G9
ROTATE __ (C)
P30G13
CW
ROTATE CW(S)
CW
ROTATE CW (S)
P46G16
CW
ROTATE CW (P)
P44G16
CW
ROTATE CW(P)

G 4 Gesture key


open hand held straight


open hand held straight
(relaxed, thumb in)


open hand held straight
(relaxed, thumb out)


pinch


pinch


pinch


full hand pinch


grasp


“U”grasp


fist


grasping a sphere


open palm facing front


open palm facing back


open hand /tight


grab the edge

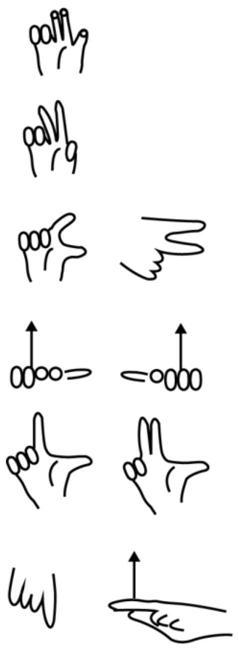

touch

wave around a point


stays static


tap

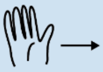
tap

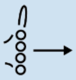


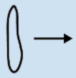
Different number of fingers
and poses used to translate
up/down/left/right

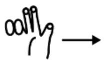
G 5 Categorised gestures and the codes assigned to them

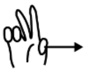
Part 1 - Translate Left


TL01.1 (13/8)
Same as TR01

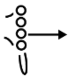

TL01.2 (12/9)
Same as TR06

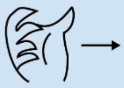

TL01.3 (7/6)
Same as TR09

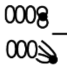

1,2 or 3 fingers
TL01.4 (4)
Same as TR02

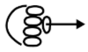

TL01.5 (2)
Same as TR07


TL01.6 (1/1)
Same as TR05

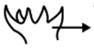

TL01.7 (1/1)


TL02.1 (8/5)
Same as TR11

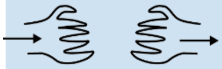

2 or 3 fingers
TL02.2 (4)
Same as TR03

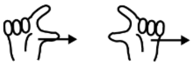

TL02.3 (2)
Same as TR12

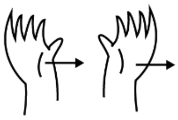

TL02.4 (1/1)
Same as TR04

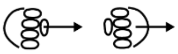

TL02.5 (1/1)
Same as TR10

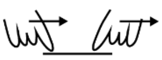

TL02.6 (1/1)
Same as TR13

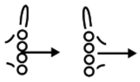

TL03.1 (11/11)
Same as TR17

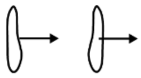

TL03.2(2/1)
Same as TR16

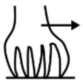

TL03.3 (2/2)
Same as TR18


TL03.4 (1/1)

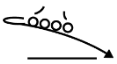

TL04.1 (2/2)
Same as TR19


TL04.2 (2/2)

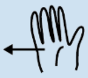

TL04.3(2/2)
Same as TR20

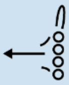

TL05 (4)
Same as TR15

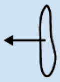

TL06 (2/1)
Same as TR14

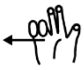

TL07 (1/1)
Same as TR08

Part 1 - Translate Right


TR01.1 (13/9)
Same as TL01

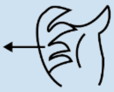

TR01.2 (11/8)
Same as TL06

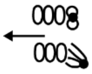

TR01.3 (9/6)
Same as TL09

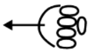

1,2 or 3 fingers
TR01.4 (4/2)
Same as TL02


TR01.5 (3/2)
Same as TL07


TR01.6 (1/1)
Same as TL05


TR02.1 (7/5)
Same as TL11

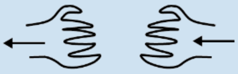

2 or 3 fingers
TR02.2 (4/3)
Same as TL03

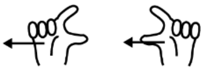

TR02.3 (1/1)
Same as TL12

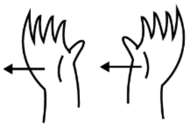

TR02.4 (4/3)
Same as TL04

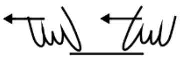

TR02.5 (2/2)
Same as TL10

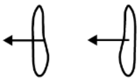

TR02.6 (1/1)
Same as TL13

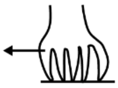

TR03.1 (9/8)
Same as TL17


TR03.2 (2/2)
Same as TL16


TR03.3 (3/3)
Same as TL18


TR04.1 (2/2)
Same as TL20


TR04.2 (1/1)
Same as TL20

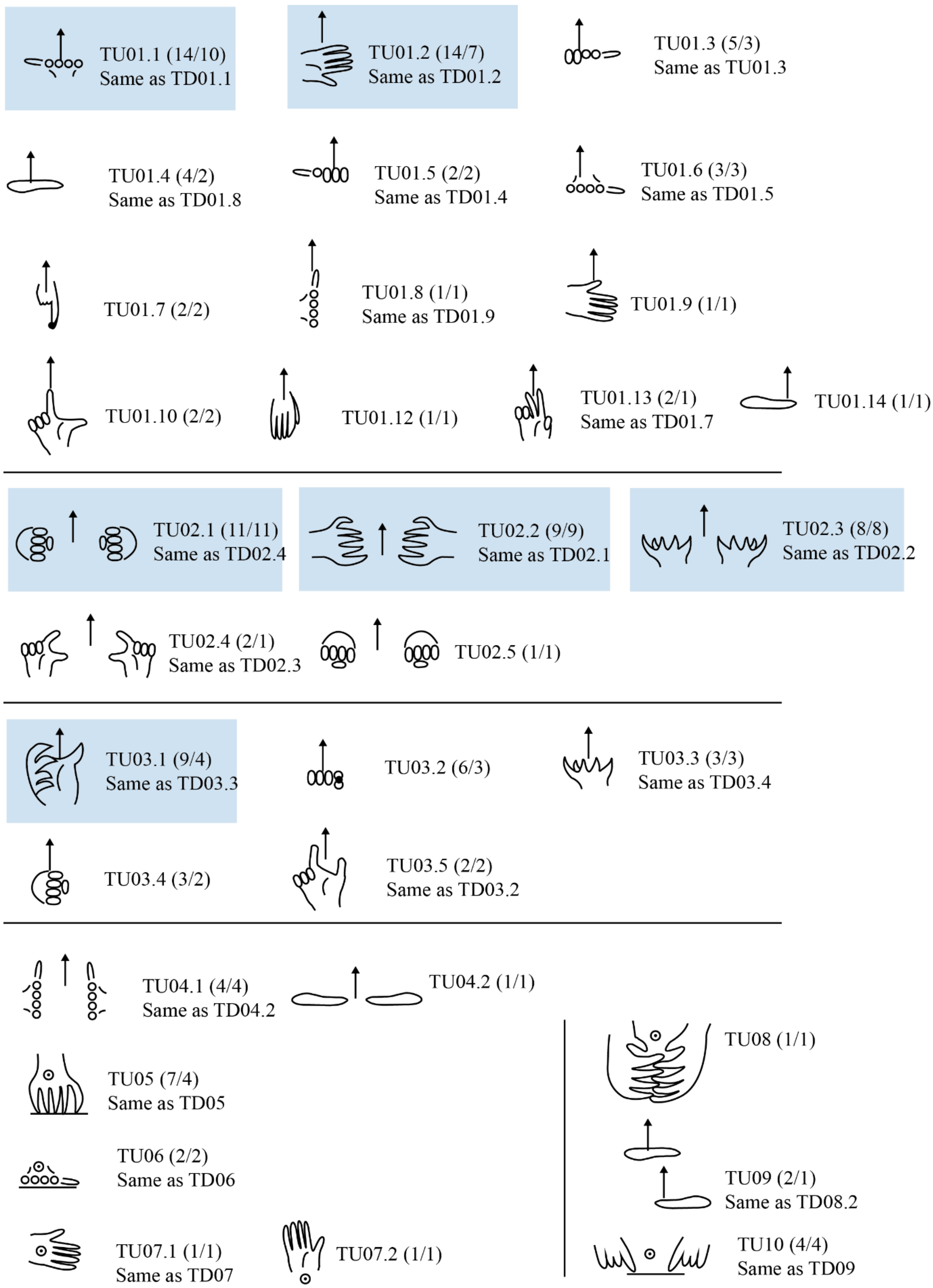

TR05 (8/6)
Same as TL15


TR06 (2/2)
Same as TL14

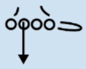

TR07 (1/1)
Same as TL08


TR08 (1/1)

Part 1 - Translate up

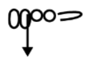


Part 1 - Translate down



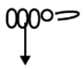
TD01.1 (17/10)
Same as TU01.1

TD01.2 (9/6)
Same as TU01.2

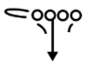


2 or 3 fingers

TD01.3 (6/4)
Same as TU01.3



TD01.4 (3/3)
Same as TU01.5

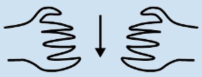


TD01.5 (1/1)
Same as TU01.6

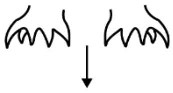
TD01.7 (1/1)
Same as TU01.13

TD01.8 (2/1)
Same as TU01.4

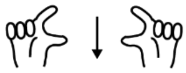
TD01.9 (1/1)
Same as TU01.8



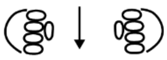
TD02.1 (12/12)
Same as TU02.2



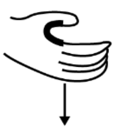
TD02.2 (1/1)
Same as TU02.2



TD02.3 (1/1)
Same as TU02.4



TD02.4 (1/1)
Same as TU02.1



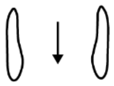
TD03.1 (3/3)

TD03.2 (3/3)
Same as TU03.5

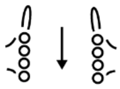
TD03.3 (3/2)
Same as TU03.1

TD03.4 (1/1)
Same as TU03.3

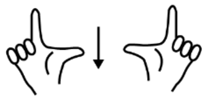
TD03.5 (2/1)
Same as TU03



TD04.1 (1/1)

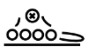


TD04.2 (1/1)
Same as TU04.1



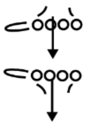
TD04.3 (1/1)

TD05 (9/6)
Same as TU05

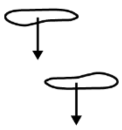


TD06 (2/2)
Same as TU06

TD07 (2/1)
Same as TU07.1



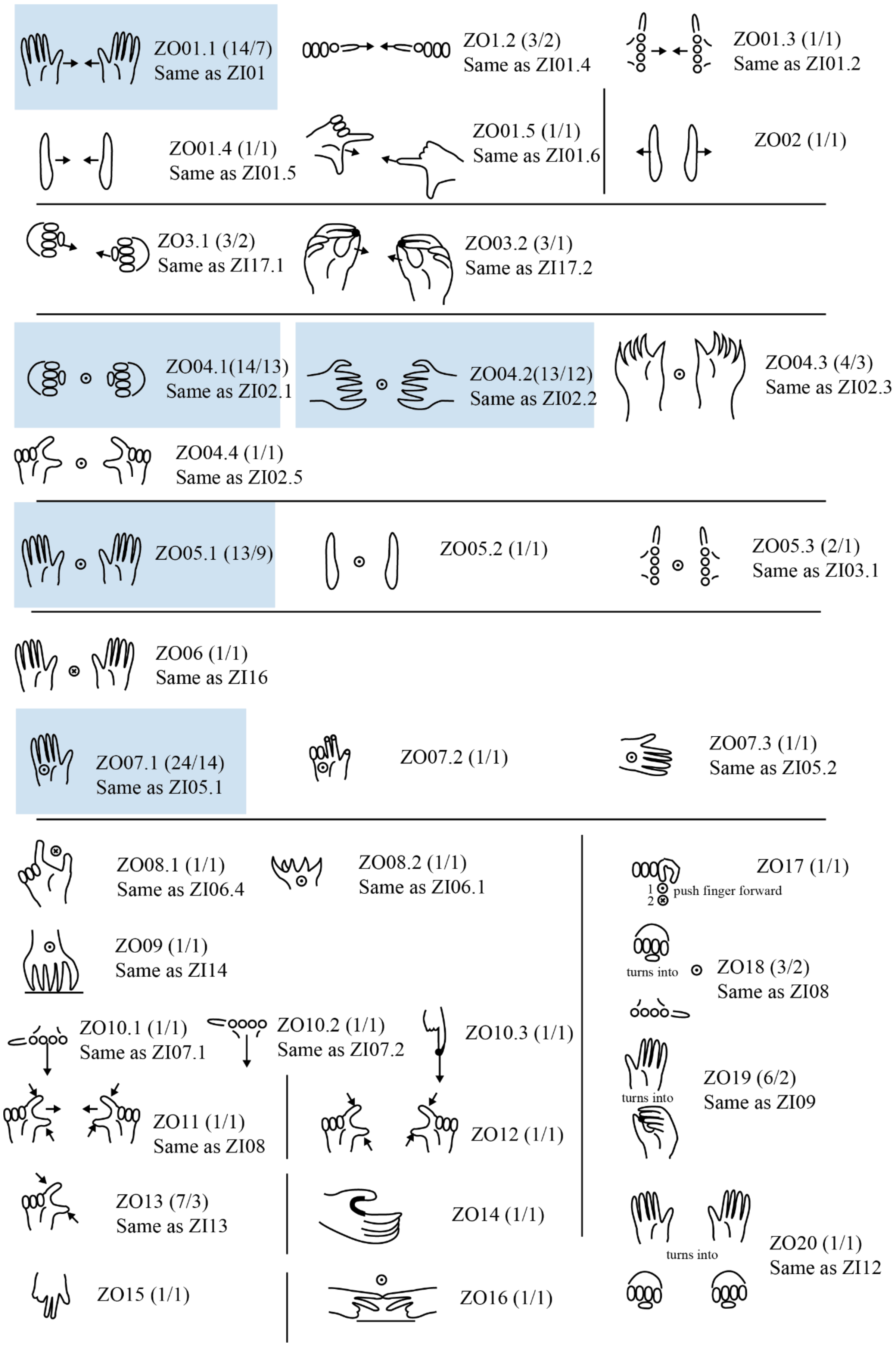
TD08.1 (1/1)



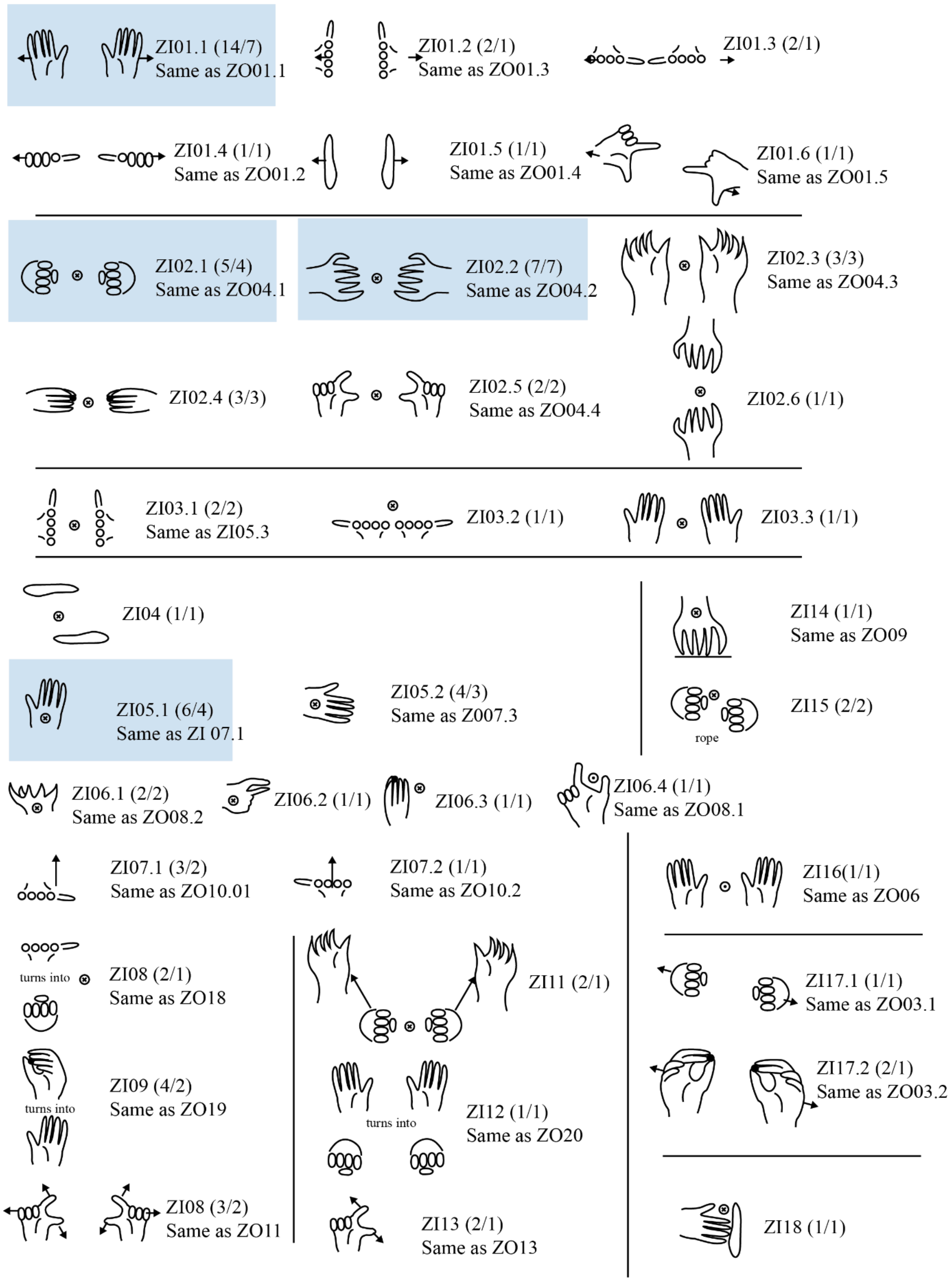
TD08.2 (1/1)
Same as TU09

TD09 (3/3)
Same as TU10

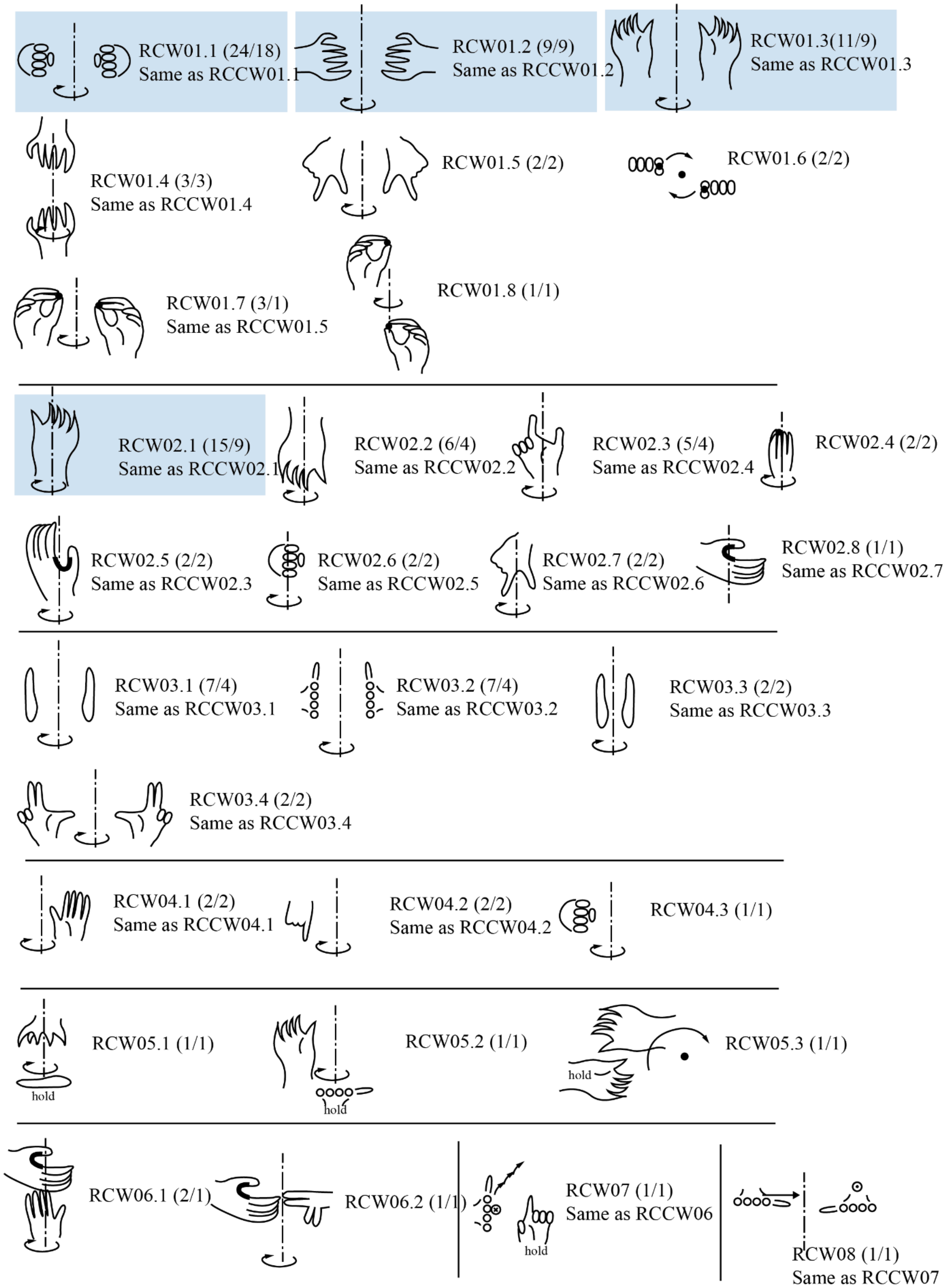
Part 1 - Zoom Out



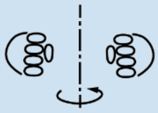
Part 1 - Zoom In

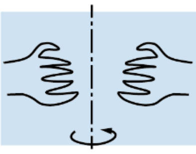


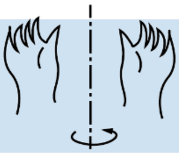
Part 1 - Rotate Clockwise



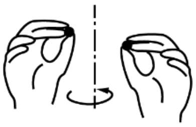
Part 1 - Rotate Counterclockwise


RCCW01.1 (15/12)
Same as RCW01.1


RCCW01.2 (10/8)
Same as RCW01.2


RCCW01.3(6/6)
Same as RCW01.3


RCCW01.4 (7/5)
Same as RCW01.4


RCCW01.5 (4/3)
Same as RCW01.7


RCCW02.1 (16/14)
Same as RCW02.1


RCCW02.2 (5/5)
Same as RCW02.2

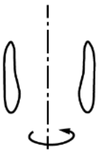

RCCW02.3 (4/4)
Same as RCW02.5

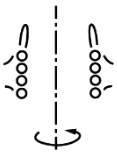

RCCW02.4 (3/3)
Same as RCW02.3


RCCW02.5 (2/2)
Same as RCW02.6

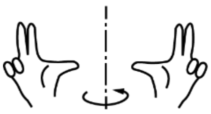

RCCW02.6 (2/2)
Same as RCW02.7


RCCW02.7 (2/2)
Same as RCW02.8


RCCW03.1 (4/4)
Same as RCW03.1


RCCW03.2 (4/3)
Same as RCW03.2


RCCW03.3 (2/2)
Same as RCW03.3

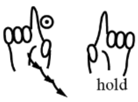

RCCW03.4 (2/2)
Same as RCW03.4


RCCW04.1 (1/1)
Same as RCW04.1

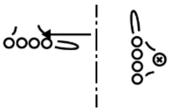

RCCW04.2 (3/1)
Same as RCW04.2


RCCW04.3 (1/1)

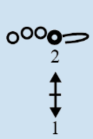

RCCW05 (1/1)



RCCW06 (1/1)
Same as RCW07

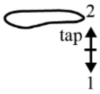

RCCW07 (1/1)
Same as RCW08

Part 1 - Deselect

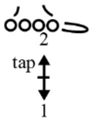


D01.1 (13/13)
Same as S01.1

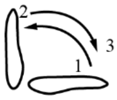
D01.2 (4/4)
Same as S01.2



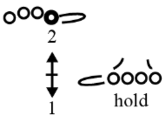
D02.1 (1/1)
Same as S2.2



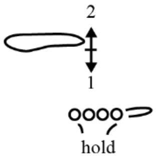
D02.2 (1/1)
Same as S2.3



D02.3 (1/1)
Same as S2.1

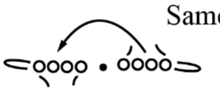


D03.1 (2/2)
Same as S03.1

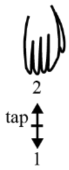


D03.2 (1/1)
Same as S03.2

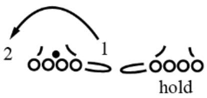
D04.1 (2/2)
Same as S06



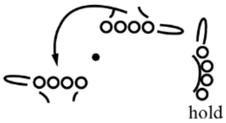
D05.1 (1/1)



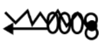
D05.2 (1/1)
Same as S11

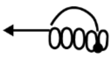


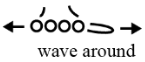
D06.1 (1/1)



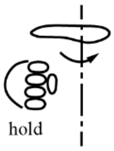
D06.2 (1/1)


D07.1 (1/1)
Same as S14

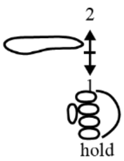

D07.2 (1/1)



D08 (3/3)

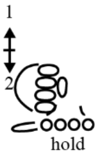


D09 (2/2)
Same as S08

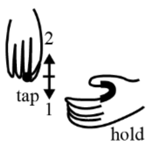


D10 (1/1)
Same as S04.1


D11(1/1)



D12 (1/1)

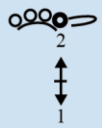


D13 (1/1)

D14 (1/1)
Same as S07

D15 (1/1)

Part 1 - Select

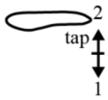


S01.1 (10/10)
Same as D01.1

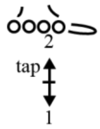
1 or 2 fingers

S01.2 (7/7)
Same as D01.2

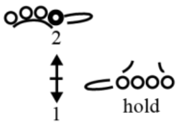
S02.1 (3/3)
Same as D02.3



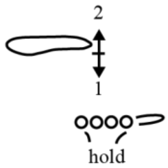
S02.2 (2/2)
Same as D02.1



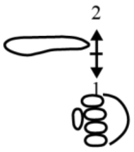
S02.3 (2/2)
Same as D02.2



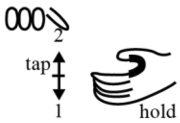
S03.1 (3/3)
Same as D03.1



S03.2 (1/1)
Same as D03.2



S04.1 (1/1)
Same as D10

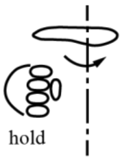


S04.2 (1/1)

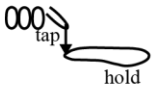
S05 (1/1)

S06 (1/1)
Same as D04.1

S07 (1/1)
Same as D14



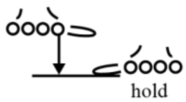
S08 (1/1)
Same as D09



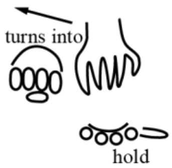
S09 (1/1)

S10 (1/1)

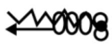
S11 (1/1)
Same as D05.2



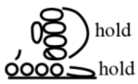
S12 (1/1)



S13 (1/1)



S14 (1/1)
Same as D07



S15 (1/1)

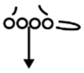
S16 (1/1)

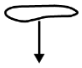
Part 1 - Extrude Cut


EC01.1 (12/12)


EC01.2 (8/8)


EC01.3 (1/1)


EC01.4 (1/1)


EC01.5 (1/1)

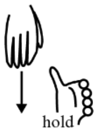

EC01.6 (1/1)


EC02.1 (2/2)


EC02.2 (1/1)

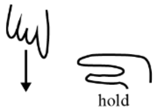

EC02.3 (1/1)


EC02.4 (1/1)

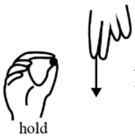


EC03.1 (1/1)

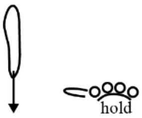
EC03.2 (1/1)



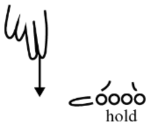
EC03.3 (1/1)



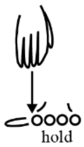
EC03.4 (1/1)



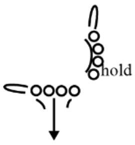
EC04.1 (2/2)



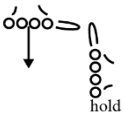
EC04.2 (1/1)



EC04.3 (1/1)



EC04.4 (1/1)



EC04.5 (1/1)

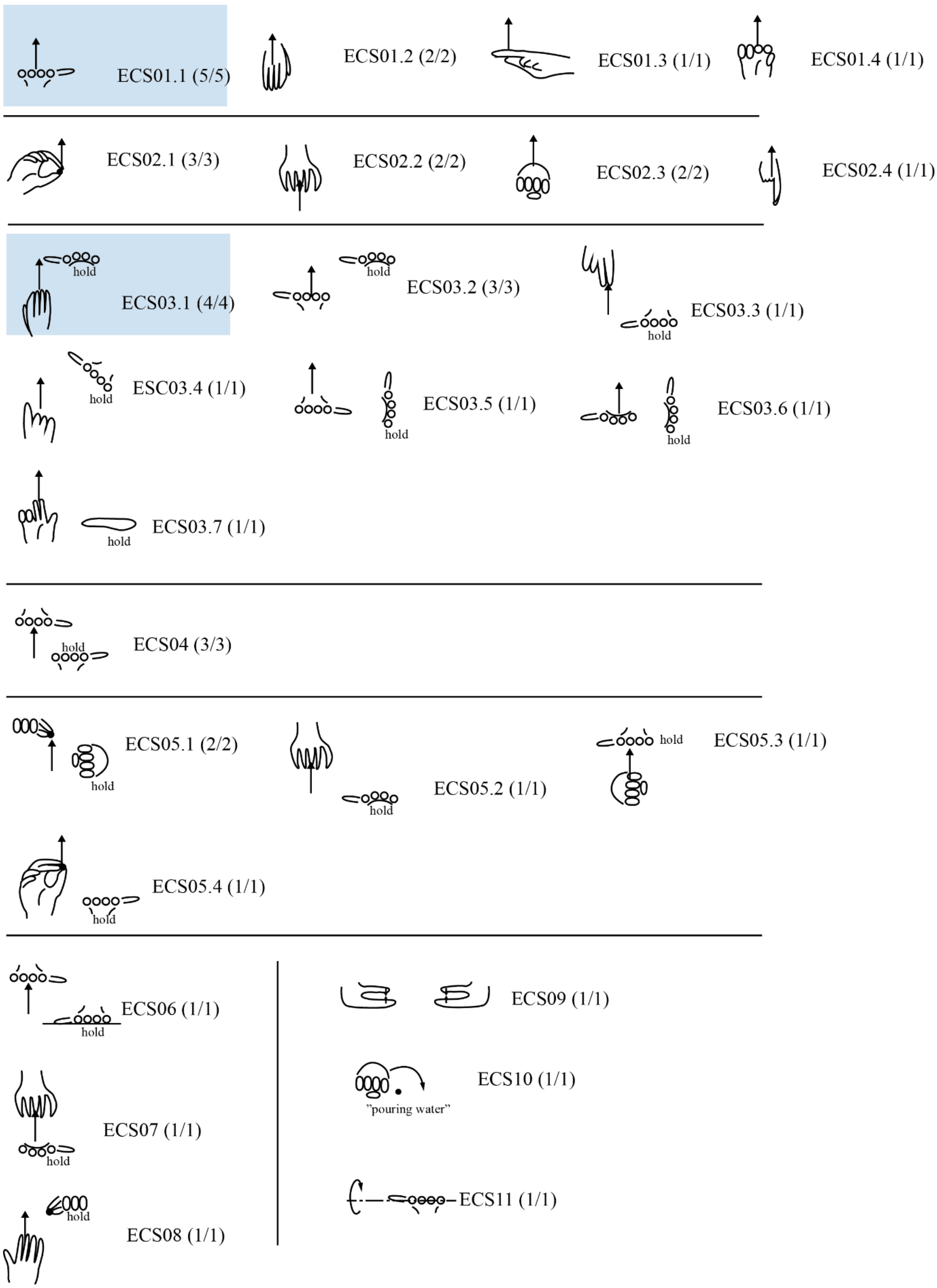
EC05.1 (1/1)

EC05.2 (1/1)


EC06 (1/1)


EC07 (1/1)

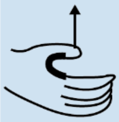
Part 1 - Extrude Cut Shallower



Part 1 - Extrude Up

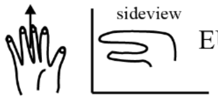
EU01.1 (4/4)
Same as ED01.3

EU01.2 (1/1)
Same as ED01.2

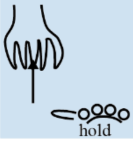


EU02.1 (8/8)
Same as ED02

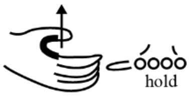
EU02.2 (2/2)



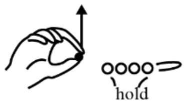
EU02.3 (1/1)



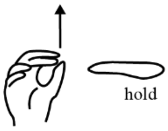
EU03.1 (5/5)



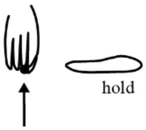
EU03.2 (3/3)



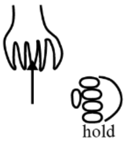
EU03.3 (2/2)
Same as ED05.1



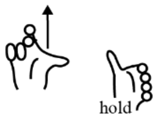
EU03.4 (1/1)



EU03.5 (1/1)

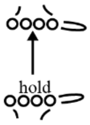


EU04.1 (2/2)

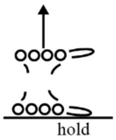


EU04.2 (1/1)

EU05.1 (2/2)

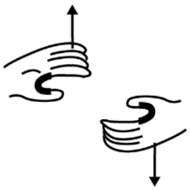


EU05.2 (1/1)
Same as ED04.2

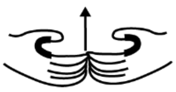


EU06 (1/1)

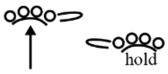
EU07 (2/2)
Same as ED18



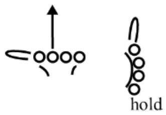
EU08 (1/1)



EU09 (1/1)

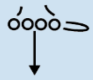


EU10.1 (3/3)
Same as ED03.1



EU10.2 (1/1)

Part 1 - Extrude Down

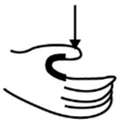


ED01.1 (8/8)

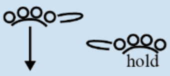
ED01.2 (6/6)
Same as EU01.2

ED01.3 (2/2)
Same as EU01.1

ED01.4 (2/2)

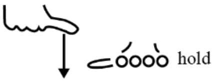


ED02 (1/1)
Same as EU02.1

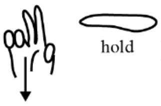


ED03.1 (6/6)
Same as EU10.1

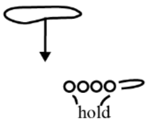
ED03.2 (1/1)



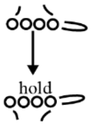
ED03.3 (1/1)



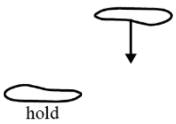
ED03.4 (1/1)



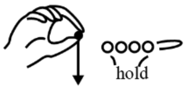
ED04.1 (3/3)



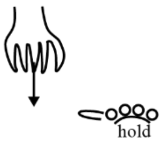
ED04.2 (2/2)
Same as EU05.2



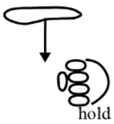
ED04.3 (2/2)



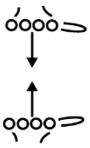
ED05.1 (1/1)
Same as EU03.3



ED05.2 (1/1)



ED06 (1/1)



ED07 (2/2)

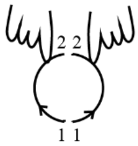
ED18 (1/1)
Same as EU07

Part 2 - Draw

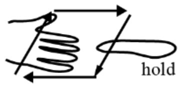

Drw01 (68/25)


Drw02 (1/1)

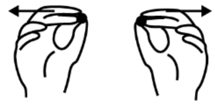

Drw03 (1/1)



Drw04 (11/10)

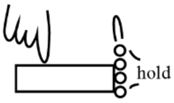


Drw05 (2/1)


Drw06 (5/3)

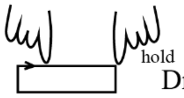
Drw07 (15/9)

Drw08 (3/3)



Drw09.1 (10/8)

hand that holds changes shapes
between different participants

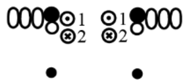


Drw09.2 (8/5)

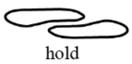
hand that holds changes shapes
between different participants


Drw10 (2/1)

Drw11 (1/1)

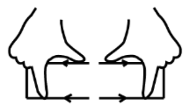


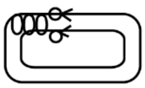
Drw12 (3/1)

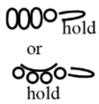


Drw13 (1/1)

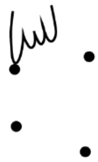

Drw14 (12/8)

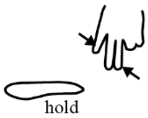

Drw15 (9/7)


Drw16 (1/1)



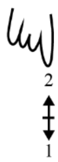
Drw17 (2/2)


Drw18 (4/1)



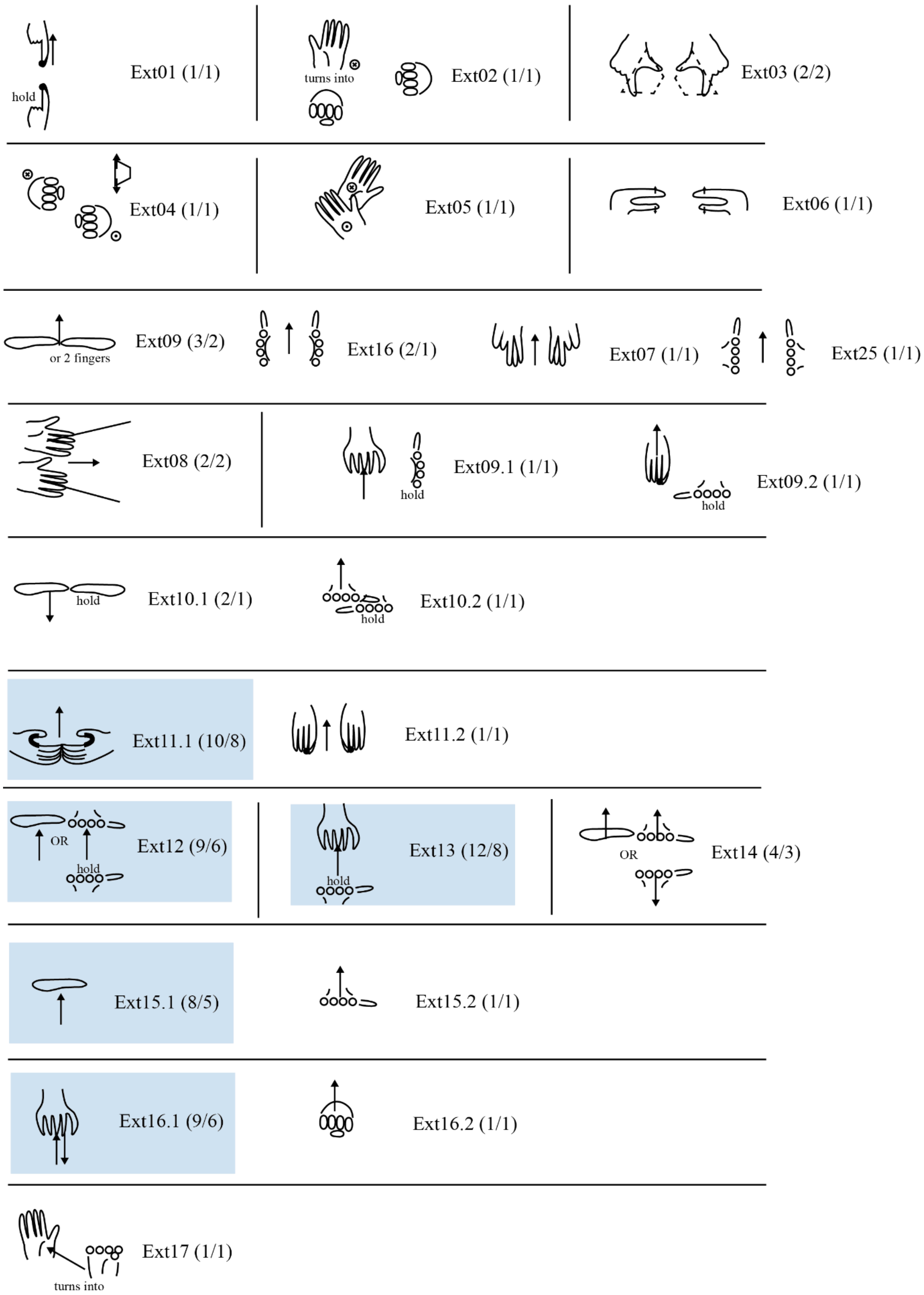
Drw19 (2/1)


Drw20 (1/1)

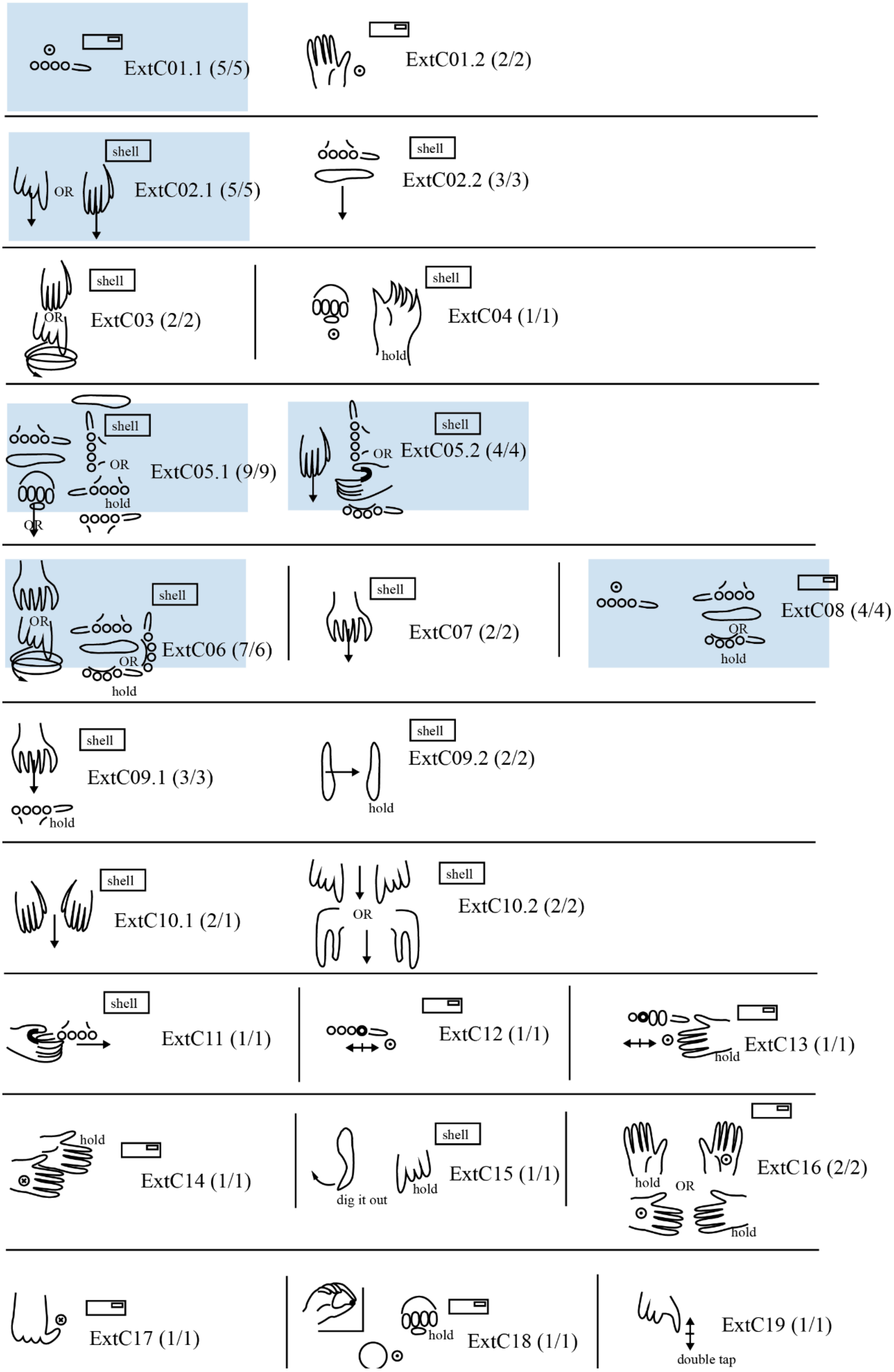


Drw21 (1/1)

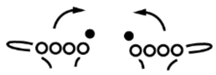
Part 2 - Extrude



Part 2 - Extrude Cut

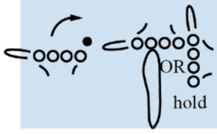


Part 2 - Bend



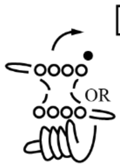
tri/hex

Ben01 (4/4)



tri/hex

Ben02 (6/6)

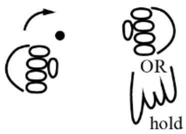


tri/hex

Ben03 (4/3)

tri

Ben04 (1/1)

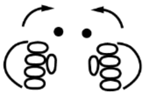


tri

Ben05.2 (2/2)

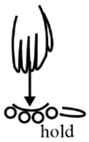
tri/hex

Ben05.1 (4/3)



hex

Ben06 (1/1)



hex

Ben07 (1/1)

hex

Ben08 (1/1)

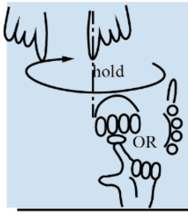
hex

Ben10 (1/1)

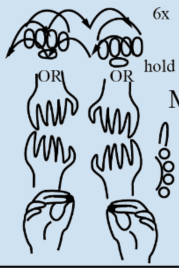
hex

Ben11 (1/1)

Part 2 - Multiply/Pattern

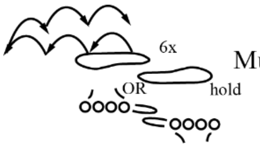


MulPat06 (5/5)

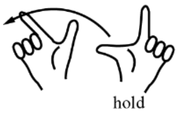


MulPat07 (6/6)

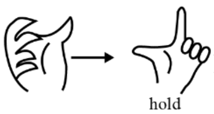
MulPat01 (2/2)



MulPat08 (2/2)

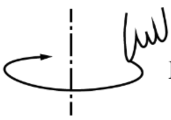


MulPat02 (1/1)

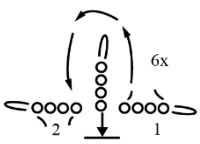


MulPat03 (1/1)

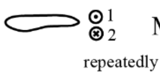
MulPat04 (1/1)



MulPat05 (1/1)

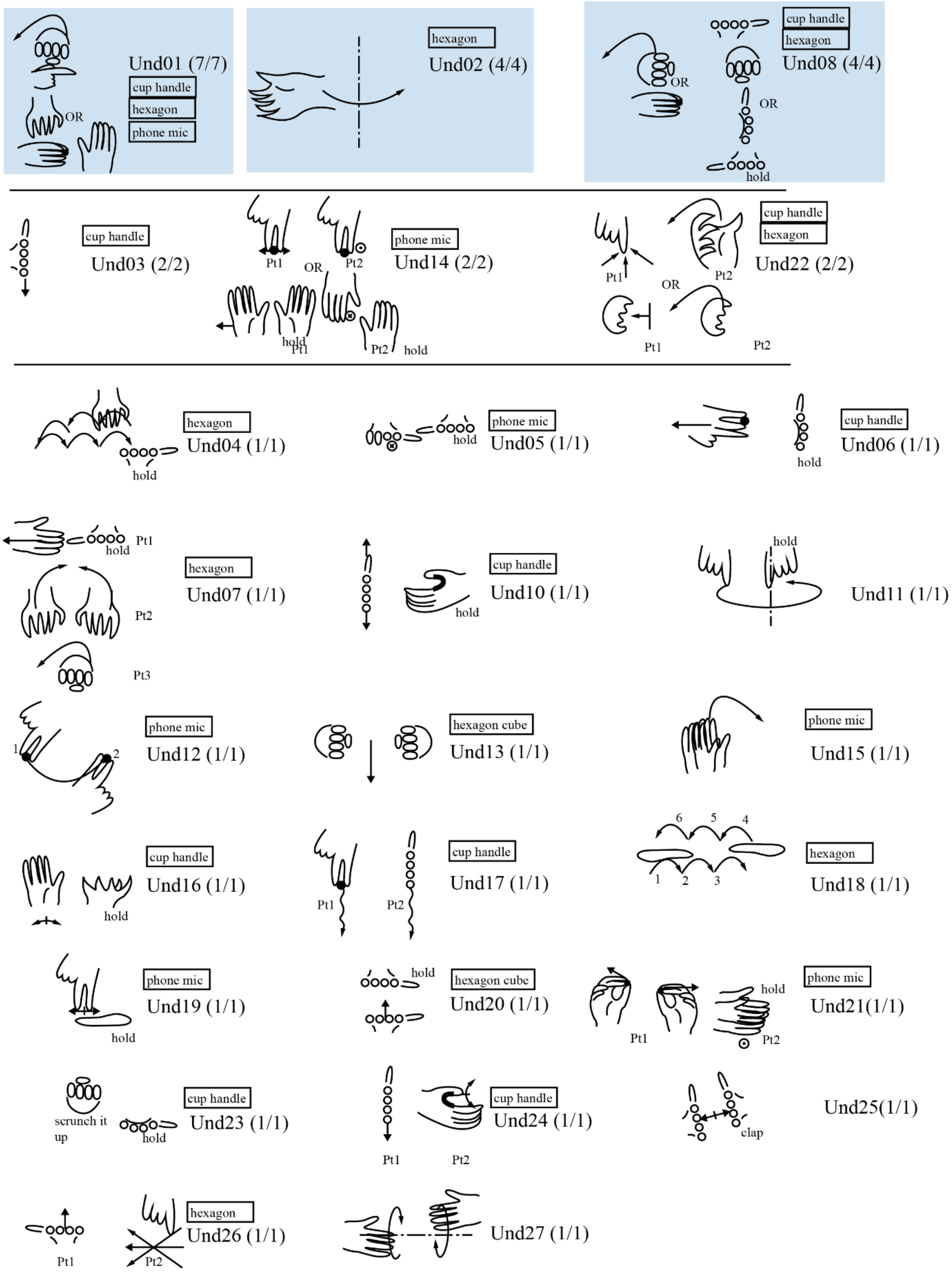


MulPat09 (1/1)

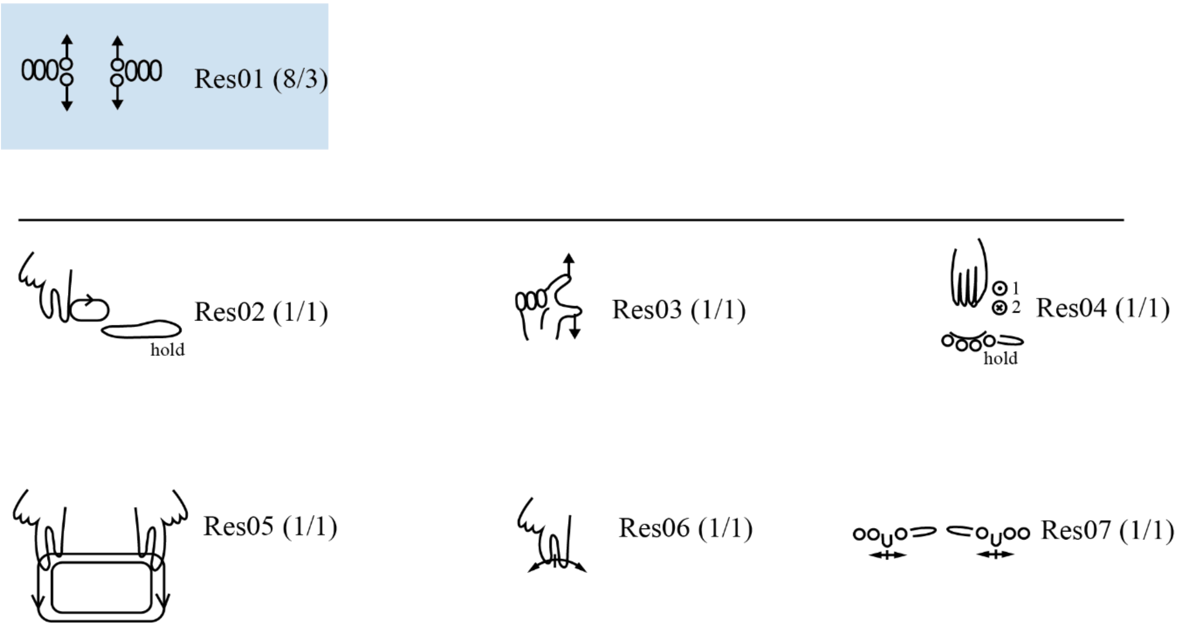


MulPat10 (1/1)

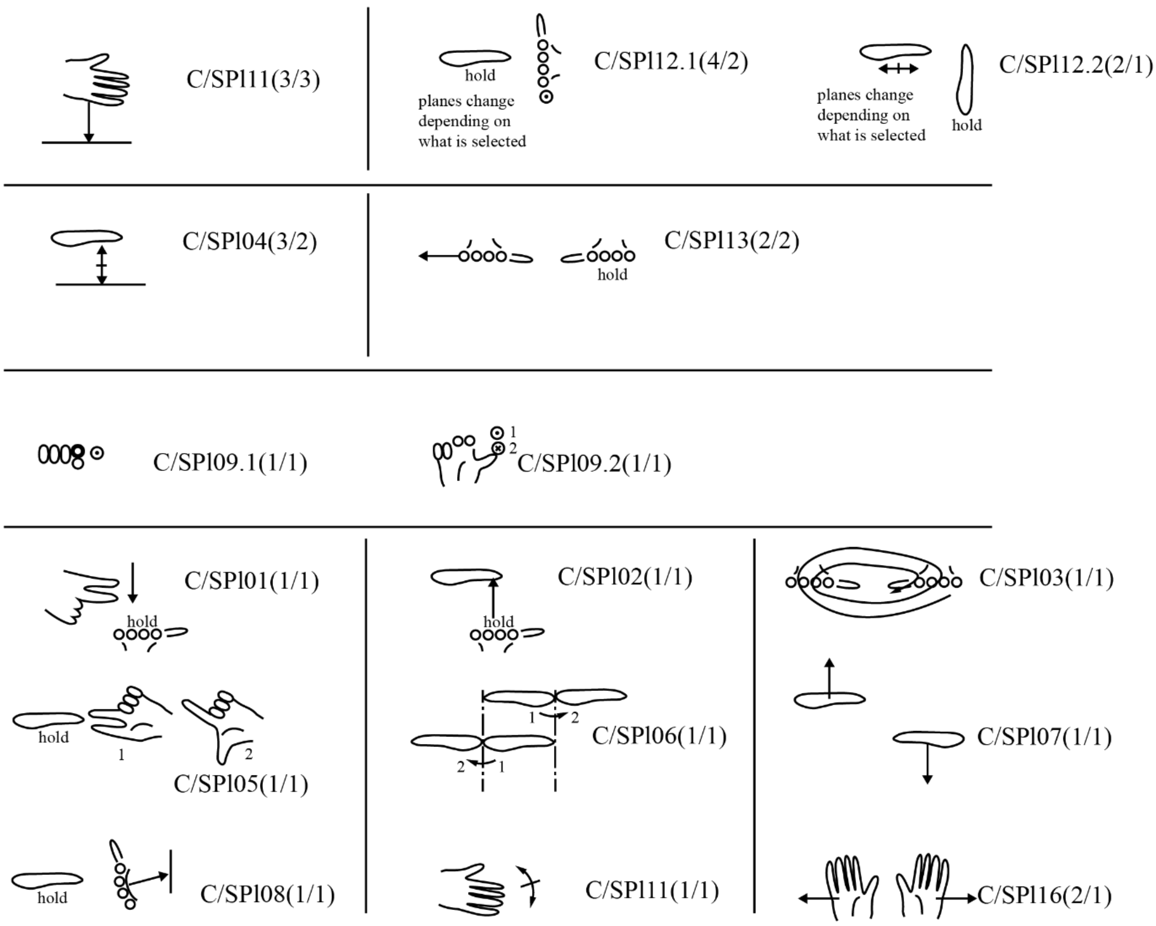
Part 2 - Undo


Und01 (7/7)
cup handle
hexagon
phone mic
OR
hexagon
Und02 (4/4)
cup handle
hexagon
Und08 (4/4)
OR
OR
hold
cup handle
Und03 (2/2)
Pt1
OR
Pt2
phone mic
Und14 (2/2)
hold
Pt1
Pt2
hold
Pt1
OR
Pt2
cup handle
hexagon
Und22 (2/2)
Pt1
Pt2
hexagon
Und04 (1/1)
hold
hold
phone mic
Und05 (1/1)
hold
cup handle
Und06 (1/1)
Pt1
hold
hexagon
Und07 (1/1)
Pt2
Pt3
cup handle
Und10 (1/1)
hold
hold
Und11 (1/1)
1
2
phone mic
Und12 (1/1)
hexagon cube
Und13 (1/1)
phone mic
Und15 (1/1)
cup handle
Und16 (1/1)
hold
Pt1
Pt2
cup handle
Und17 (1/1)
6
5
4
1
2
3
hexagon
Und18 (1/1)
phone mic
Und19 (1/1)
hold
hold
hexagon cube
Und20 (1/1)
hold
Pt1
Pt2
phone mic
Und21(1/1)
scrunch it up
hold
cup handle
Und23 (1/1)
cup handle
Und24 (1/1)
Pt1
Pt2
clap
Und25(1/1)
Pt1
Pt2
hexagon
Und26 (1/1)
Und27 (1/1)

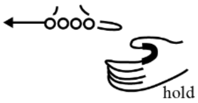
Part 2 - Resize



Part 2 - Create-Select Plane



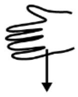
Part 2 - End the Extrude



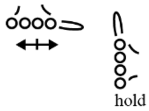
EExt05.1(2/1)

EExt05.2(1/1)

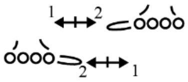
EExt01(1/1)



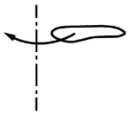
EExt02(1/1)



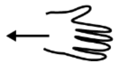
EExt03(1/1)



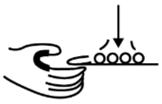
EExt04(1/1)



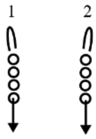
EExt06(1/1)



EExt07(1/1)

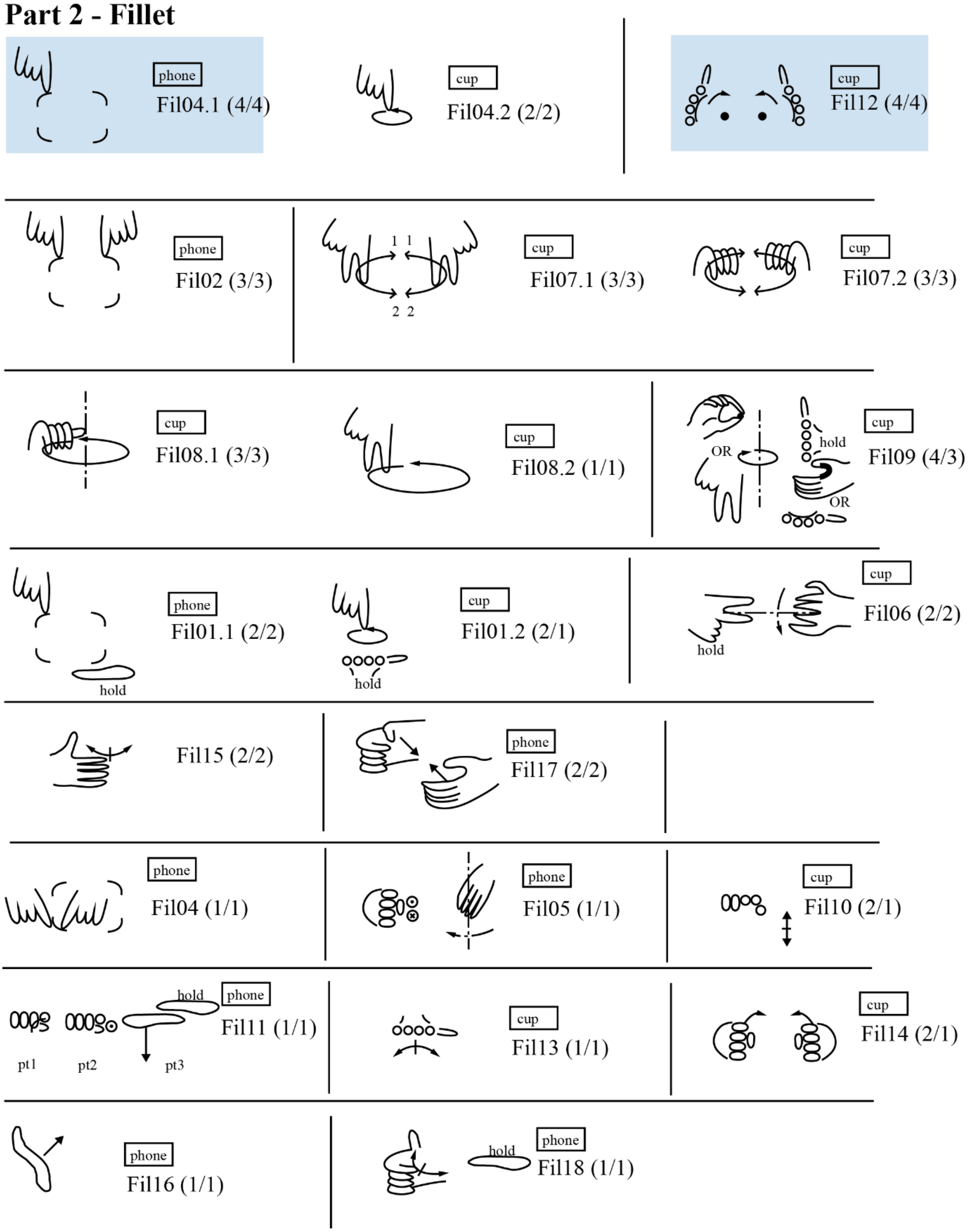


EExt08(1/1)

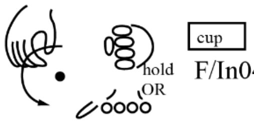


EExt09(1/1)

Part 2 - Fillet



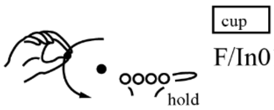
Part 2 - Fill in



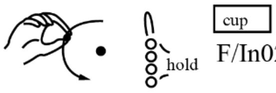
F/In04.1 (2/2)

F/In04.2 (2/2)

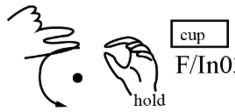
F/In06 (2/2)



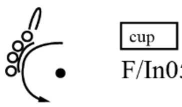
F/In01 (1/1)



F/In02 (1/1)

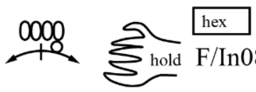


F/In03 (1/1)

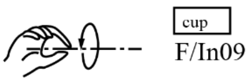


F/In05 (1/1)

F/In07 (1/1)

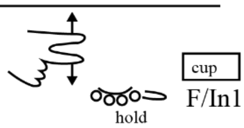


F/In08 (1/1)



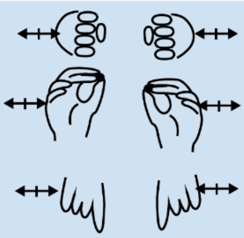
F/In09 (1/1)

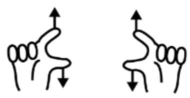
F/In10 (1/1)



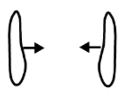
F/In11 (1/1)

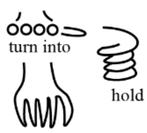
Part 2 - Scale


Scl01 (3/3)


Scl02 (2/2)

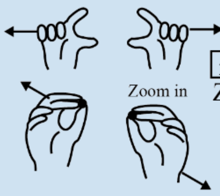

Scl03 (1/1)


Scl04 (1/1)



Scl05 (1/1)

Part 2 - Zoom



phone

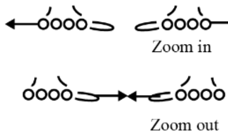
Zoom06 (4/4)

phone cup

Zoom05 (3/3)

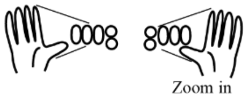
cup

Zoom07.1 (3/3)



phone

Zoom07.2 (5/2)

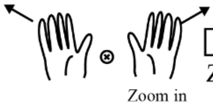


phone hex

Zoom09 (2/2)

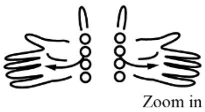
phone

Zoom01 (1/1)



cup

Zoom02 (1/1)

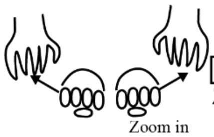


cup

Zoom03 (1/1)

phone

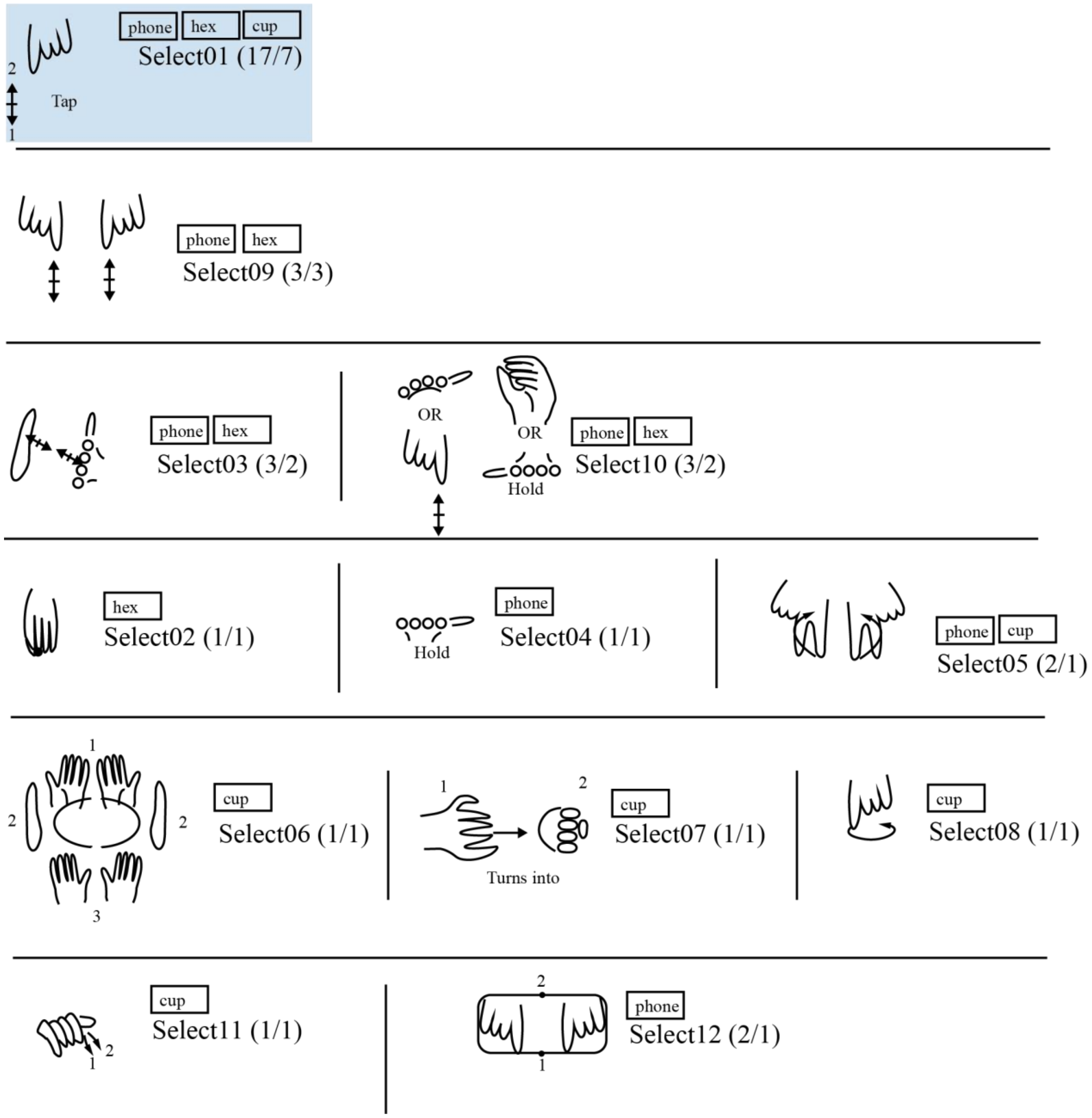
Zoom04 (1/1)



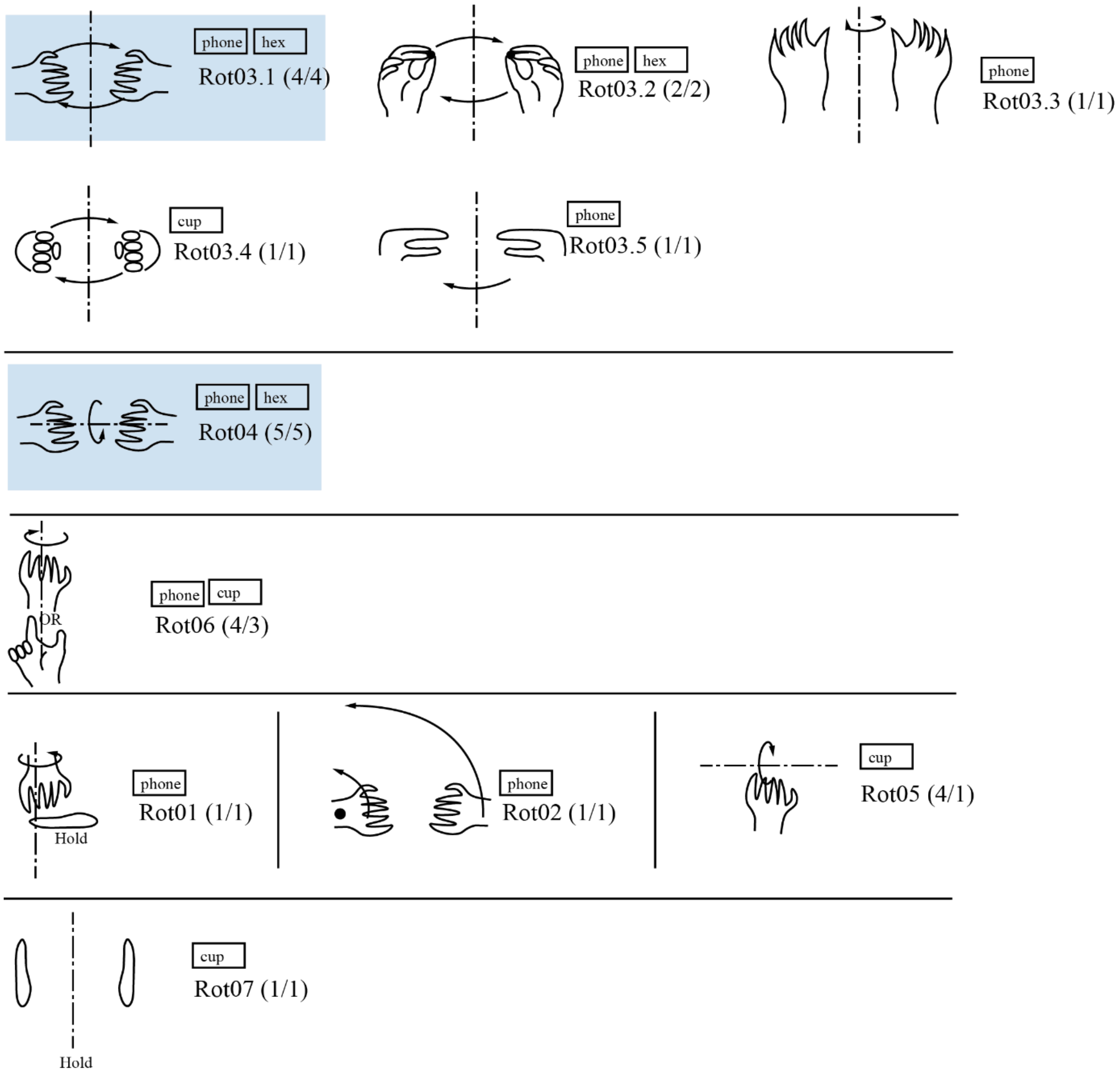
phone

Zoom08 (1/1)

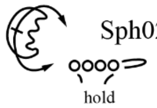
Part 2 - Select



Part 2 - Rotate



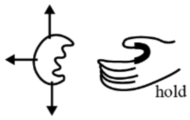
Part 2 - Sphere



Sph02(2/2)

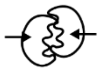

Sph01(1/1)

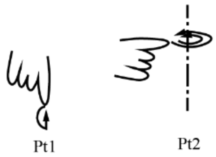
Sph03(1/1)



Sph04(1/1)

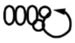

Sph05(1/1)

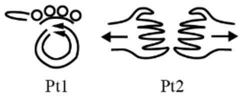

Sph06(1/1)



Sph07(1/1)

Sph08(1/1)


Sph09(1/1)

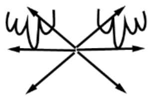


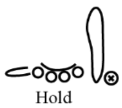
Sph10(1/1)

Sph11(1/1)

Part 2 - Slice

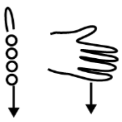

hex
Slice03 (4/4)


hex
Slice01 (1/1)

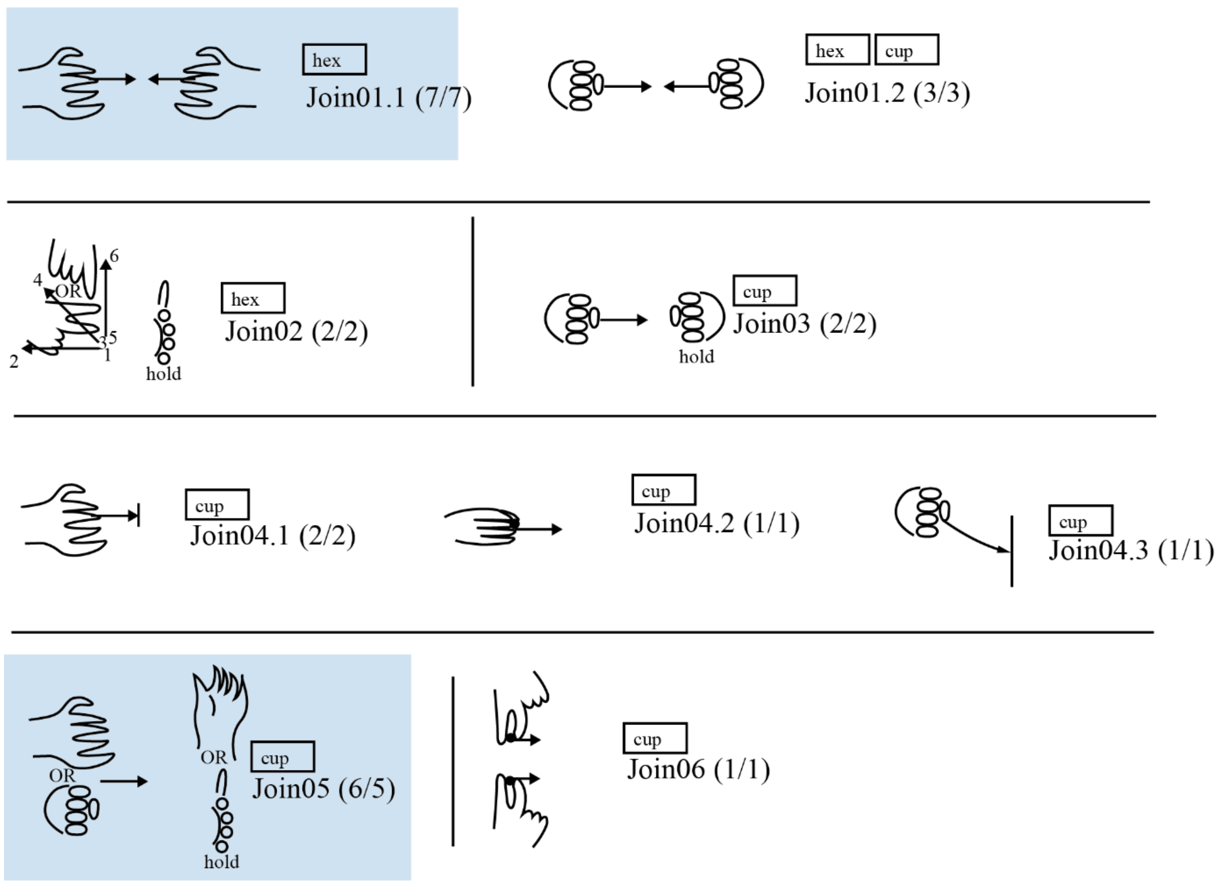


hex
Slice02 (1/1)

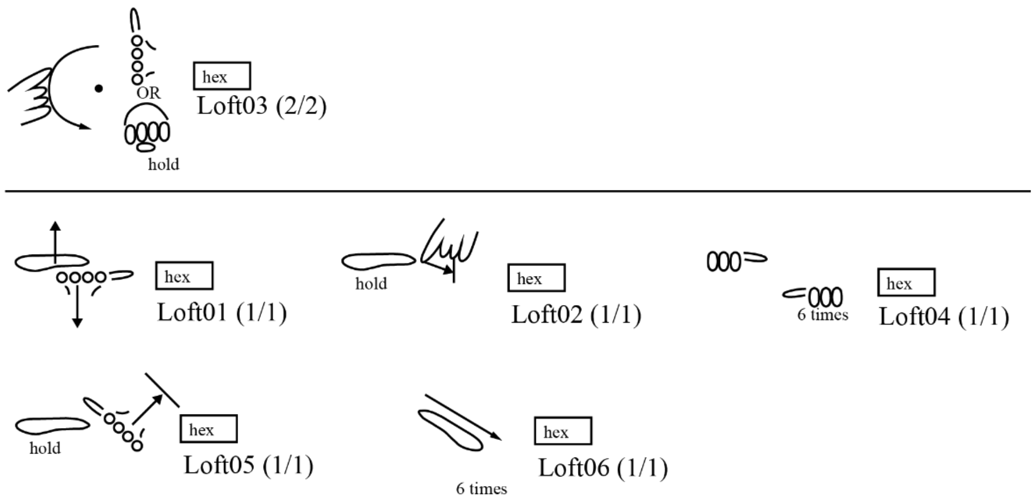
hex
Slice04 (1/1)


hex
Slice05 (1/1)

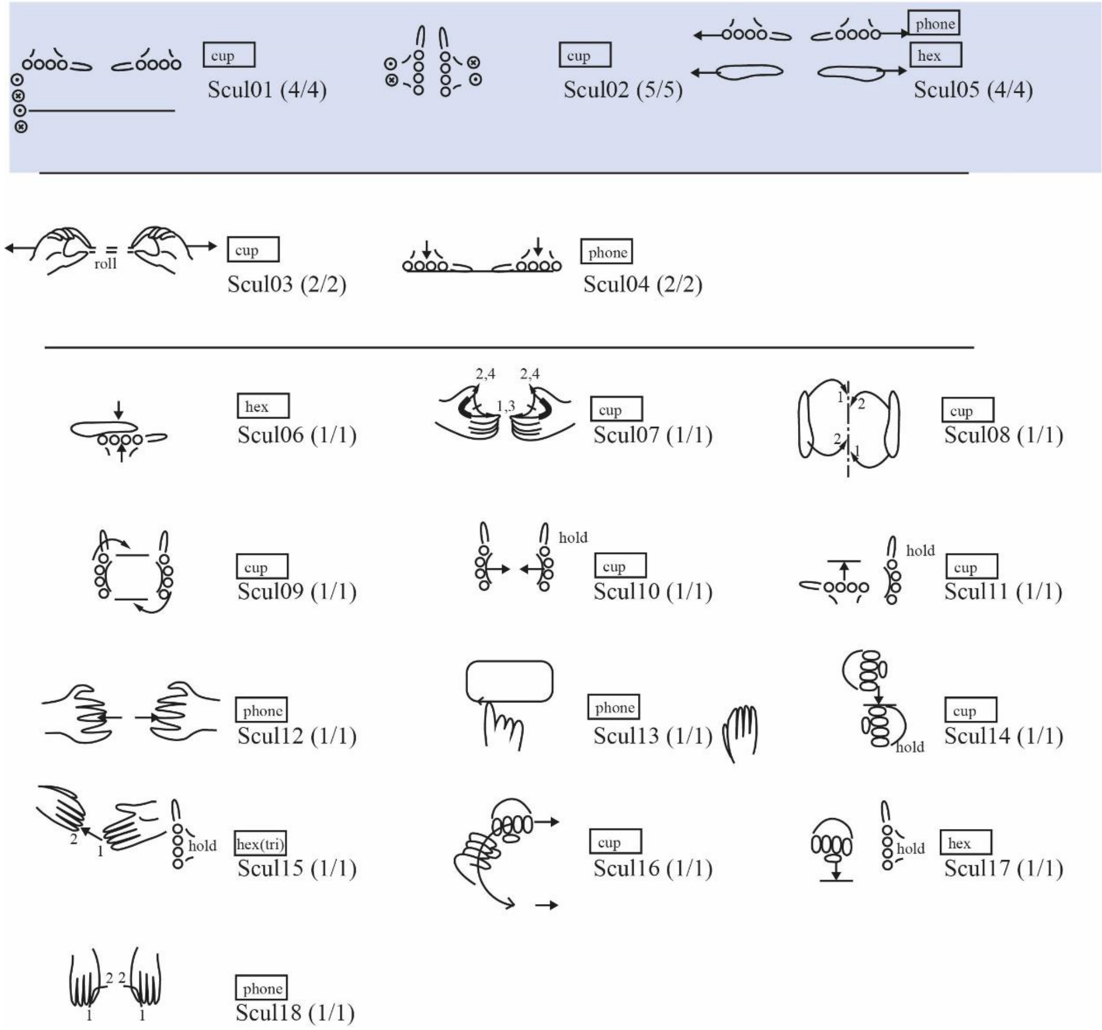
Part 2 - Join



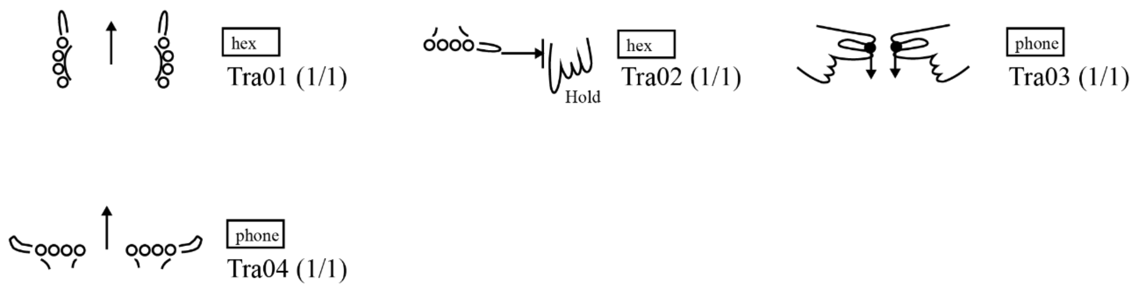
Part 2 - Loft



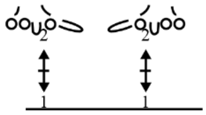
Part 2 - Sculpt



Part 2 - Translate



Part 2 - Copy

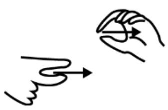

Copy01 (1/1)

Part 2 - Start Sketch


SS01(4/1)

Snap fingers
to indicate
sketching

Part 2 - Stick


Stick01 (1/1)

G 6 Comparison of gestures performed by the same participants for different objects during the same activities

Table 24 : Zoom out activity for the chair, the phone and the sphere

ACTIVITY: ZOOM OUT

	Same gesture performed for					
Participant	phone and sphere	all three objects	phone and chair, but not sphere	phone and sphere, but not chair	Unique number	Equivalent to
P01	y	n	n	y	ZO29	ZI30
P02		n	n	n	ZO21	ZI20
P03		y	n	n	ZO01	ZI01
P04					ZO18	ZI18
P05	n	n	y	n	ZO17	ZI17
P06	n	n	n	n	ZO12	
P07	y	n	n	y	ZO18	ZI18
P08	n	n	n	n	ZO11	ZI11
P09	y	n	n	y	ZO29	ZI30
P10		n	n	n	ZO18	ZI18
P11	n	n	n	n	ZO29	ZI30
P12		y	n	n	ZO07	ZI07
P13	n	n	y	n	ZO31	ZI31
P14		n	n	n	ZO16	ZI16
P15	n	n	n	n	ZO17	ZI17
P16	n	n	n	n	ZO20	ZI19
P17	n	n	n	n	ZO17	ZI17
P18	n	n	n	n	ZO01	ZI01
P19	n	n	y	n	ZO29	ZI30
P20		n	n	n	ZO16	ZI16
P21	y	n	n	y	ZO13	ZI13
P22		n	n	n	ZO17	ZI17
P23	y	y	n	n	ZO29	ZI30
P24		n	n	n	ZO16	ZI16
P25	y	n	n	y	ZO29	ZI30

ACTIVITY: ZOOM OUT

	Same gesture performed for					
Participant	phone and sphere	all three objects	phone and chair, but not sphere	phone and sphere, but not chair	Unique number	Equivalent to
P26	y	y	n	n	ZO01	ZI01
P27	n	n	n	n	ZO13	ZI13
P28	y	y	n	n	ZO32	ZI34
P29	n	n	n	n	ZO29	ZI30
P30		n	n	n	ZO18	ZI18
P31	y	n	n	y	ZO32	ZI34
P32		n	n	y	ZO04	ZI05
P33	n	n	y	n	ZO25	
P34		n	n	y	ZO17	ZI17
P35	y	y	n	n	ZO18	ZI18
P36	y	y	n	n	ZO14	ZI14
P37	n	n	y	n	ZO15	ZI15
P38	n	n	n	n	ZO35	ZI36
P39	n	n	n	n	ZO06	
P40		y	n	n	ZO01	ZI01
P41	n	n	n	n	ZO33	
P42		n	n	y	ZO18	ZI18
P43	n	n	n	n	ZO05	ZI06
P44	y	y	n	n	ZO14	ZI14
	12	9	5	9		

Table 25 : Translate up activity for the chair, the phone and the sphere

ACTIVITY: TRANSLATE UP

	Same gesture performed for					
Participant	phone and sphere	all three objects	phone and chair, but not sphere	phone and sphere, but not chair	Unique number	Equivalent to
P01	y	n	n	y	TU24	TD20
P02		n	n	n	TU08	
P03		n	y	n	TU10	
P04	n	n	y	n	TU07	

ACTIVITY: TRANSLATE UP

	Same gesture performed for					
Participant	phone and sphere	all three objects	phone and chair, but not sphere	phone and sphere, but not chair	Unique number	Equivalent to
P05	n	n	n	n	TU12	
P06	y	y	n	n	TU13	
P07	y	y	n	n	TU10	
P08		n	n	n	TU16	TD12
P09		n	n	n	TU20	TD18
P10		n	n	n	TU20	TD18
P11	n	n	n	n	TU03	
P12		n	n	y	TU02	
P13	n	n	y	n	TU08	
P14		n	n	n	TU16	TD12
P15	n	n	n	n	TU15	TD11
P16	n	n	n	n	TU15	TD11
P17	n	n	n	n	TU16	TD12
P18		n	n	n	TU08	
P19		n	n	n	TU20	TD18
P20		n	n	n	TU20	TD18
P21	n	n	n	n	TU09	
P22		n	n	n	TU20	TD18
P23	n	n	n	n	TU27	
P24		n	n	n	TU16	TD12
P25	n	n	n	n	TU16	TD12
P26	y	y	n	n	TU10	
P27	n	n	y	n	TU02	
P28		n	y	n	TU28	TD21
P29		n	n	y	TU16	TD12
P30		n	n	n	TU30	
P31	n	n	n	n	TU12	
P32		y	n	n	TU02	
P33	n	n	n	n	TU25	
P34		n	y	n	TU19	TD16
P35	y	y	n	n	TU03	
P36	y	y	n	n	TU24	TD20
P37	n	n	n	n	TU31	TD23
P38		n	n	n	TU22	

ACTIVITY: TRANSLATE UP

Participant	Same gesture performed for: phone and sphere	all three objects	phone and chair, but not sphere	phone and sphere, but not chair	Unique number	Equivalent to
P39		y	n	n	TU31	TD23
P40		n	y	n	TU24	TD20
P41	y	n	n	y	TU25	
P42		y	n	n	TU25	
P43	n	n	n	n	TU32	TD24
P44	n	n	y	n	TU10	
	7	8	8	4		

Table 26 : Rotate CW activity for the chair, the phone and the sphere

ACTIVITY: ROTATE CW

Participant	Same gesture performed for: phone and sphere	all three objects	phone and chair, but not sphere	phone and sphere, but not chair	Unique number	Equivalent to
P01	n	n	n	n	RCW30	RCCW22
P02		n	n	n	RCW12	RCCW10
P03	n	n	n	n	RCW01	RCCW01
P04	y	n	n	y	RCW03	RCCW03
P05		n	y	n	RCW19	RCCW16
P06	y	y	n	n	RCW20	RCCW17
P07	n	n	n	n	RCW14	RCCW12
P08	n	n	y	n	RCW19	RCCW16
P09	n	n	n	n	RCW01	RCCW01
P10	n	n	y	n	RCW19	RCCW16
P11	n	n	n	n	RCW13	RCCW11
P12		y	n	n	RCW21	RCCW18
P13		n	n	n	RCW01	RCCW01
P14	n	n	n	n	RCW19	RCCW16
P15	n	n	n	n	RCW16	RCCW14

ACTIVITY: ROTATE CW

	Same gesture performed for					
Participant	phone and sphere	all three objects	phone and chair, but not sphere	phone and sphere, but not chair	Unique number	Equivalent to
P16	n	n	y	n	RCW01	RCCW01
P17	n	n	n	n	RCW24	
P18	n	n	n	n	RCW25	RCCW20
P19	n	n	n	n	RCW03	RCCW03
P20	y				RCW17	
P21	n	n	n	n	RCW13	RCCW11
P22		n	n	n	RCCW10	RCW12
P23		n	y	n	RCCW16	RCW19
P24	n	n	n	n	RCW03	RCCW03
P25	n	n	n	n	RCW06	RCCW06
P26	n	n	y	n	RCW07	RCCW09
P27	n	n	n	n	RCW08	
P28	n	n	y	n	RCW05	RCCW05
P29	n	n	n	n	RCW13	RCCW11
P30	n	n	n	n	RCW05	RCCW05
P31	n	n	n	n	NG	
P32		n	n	y	RCW29	
P33		n	n	n	RCW01	RCCW01
P34	n	n	n	n	RCW13	RCCW11
P35	y	y	n	n	RCW01	RCCW01
P36	n	n	n	n	RCW12	RCCW10
P37	y	y	n	n	RCW15	RCCW13
P38	n	n	y	n	RCW19	RCCW16
P39	y	y	n	n	RCW01	RCCW01
P40	n	n	n	n	RCW19	RCCW16
P41	n	n	n	n	RCW14	RCCW12
P42	n	n	n	n	RCW15	RCCW13
P43	y	n	n	y	RCW19	RCCW16
P44	n	n	n	n	RCW14	RCCW12
	7	5	8	3		

Table 27 : Rotate CW/CCW activity for the phone and the sphere

ACTIVITY: ROTATE CCW

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P01G11	n	RCCW12	RCW14
P01G20	n	RCCW22	RCW30?
P02G12	n	RCCW13	RCW15
P02G18	n	RCCW14	RCW16
P03G14	n	RCCW15	RCW18
P03G15	n	RCCW18	RCW21
P04G11		RCCW03	RCW03
P05G05	n	RCCW11	RCW13
P05G11	n	RCCW16	RCW19
P06G01	y	RCCW17	RCW20
P06G25	y	RCCW17	RCW20
P07G06	n	RCCW12	RCW14
P07G21	n	RCCW19	
P08G06	y	RCCW16	RCW19
P08G07	y	RCCW16	RCW19
P09G04	n	RCCW07	RCW09
P09G07	n	RCCW01	RCW01
P10G01	n	RCCW01	RCW01
P10G21	n	RCCW16	RCW19
P11G11	n	RCCW03	RCW03
P11G20	n	RCCW11	RCW13

ACTIVITY: ROTATE CW

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P01G16	n	RCW25	RCCW20
P02G22	n	RCW04	RCCW04
P02G25	n	RCW15	RCCW13
P03G01	n	RCW01	RCCW01
P03G11	n	RCW18	RCCW15
P04G05	y	RCW03	RCCW03
P04G06	y	RCW03	RCCW03
P05G20	n	RCW12	RCCW10
P05G22	n	RCW19	RCCW16
P06G05	y	RCW20	RCCW17
P06G16	y	RCW20	RCCW17
P07G03	n	RCW14	RCCW12
P07G22	n	RCW13	RCCW11
P08G11	n	RCW19	RCCW16
P08G21	n	RCW13	RCCW11
P09G15	n	RCW01	RCCW01
P09G24	n	RCW09	RCCW07
P10G12	n	RCW19	RCCW16
P10G13	n	RCW01	RCCW01
P11G01	n	RCW13	RCCW11
P11G16	n	RCW06	RCCW06

ACTIVITY: ROTATE CCW

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P12G12	y	RCCW18	RCW21
P12G18	y	RCCW18	RCW21
P13G05	n	RCCW01	RCW01
P13G11	n	RCCW02	RCW02
P14G14	n	RCCW01	RCW01
P14G15	n	RCCW16	RCW19
P15G11	n	RCCW14	RCW16
P15G23	n	RCCW10	RCW12
P16G01	n	RCCW11	RCW13
P16G25	n	RCCW01	RCW01
P17G06	n	RCCW12	RCW14
P17G21	n	RCCW05	RCW05
P18G06	n	RCCW20	RCW25
P18G07	n	RCCW07	RCW09
P19G04	n	RCCW16	RCW19
P19G07	n	RCCW03	RCW03
P20G01		RCCW12	RCW14
P21G11	y	RCCW01	RCW01
P21G20	y	RCCW01	RCW01
P22G12	n	RCCW10	RCW12
P22G18	n	RCCW16	RCW19
P23G05	n	RCCW17	RCW20
P23G11	n	RCCW04	RCW04

ACTIVITY: ROTATE CW

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P12G22	y	RCW21	RCCW18
P12G25	y	RCW21	RCCW18
P13G20	n	RCW01	RCCW01
P13G22	n	RCW02	RCCW02
P14G01	n	RCW19	RCCW16
P14G11	n	RCW13	RCCW11
P15G05	n	RCW16	RCCW14
P15G06	n	RCW22	
P16G05	n	RCW01	RCCW01
P16G16	n	RCW19	RCCW16
P17G03	n	RCW24	
P17G22	n	RCW05	RCCW05
P18G11	n	RCW25	RCCW20
P18G21	n	RCW01	RCCW01
P19G15	n	RCW03	RCCW03
P19G24	n	RCW19	RCCW16
P20G12	y	RCW17	
P20G13	y	RCW17	
P21G01	n	RCW13	RCCW11
P21G16	n	RCW08	
P22G22	n	RCW19	RCCW16
P22G25	n	RCW12	RCCW10
P23G20	n	RCW20	RCCW17

ACTIVITY: ROTATE CCW

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P24G14	n	RCCW03	RCW03
P24G15	n	RCCW16	RCW19
P25G11	n	RCCW06	RCW06
P25G23	n	RCCW10	RCW12
P26G01	n	RCCW09	RCW07
P26G25	n	RCCW13	RCW15
P27G06	n	RCCW01	RCW01
P27G21	n	RCCW03	RCW03
P28G06	n	RCCW05	RCW05
P28G07	n	RCCW01	RCW01
P29G04	n	RCCW05	RCW05
P29G07	n	RCCW11	RCW13
P30G01	n	RCCW02	RCW02
P30G21	n	RCCW06	RCW06
P31G11	n	RCCW02	RCW02
P31G20	n	RCCW01	RCW01
P32G12	n	RCCW11	RCW13
P32G18	n	RCCW20	RCW25
P33G05	n	RCCW01	RCW01
P33G11	n	RCCW04	RCW04
P34G14	n	RCCW10	RCW12
P34G15	n	RCCW18	RCW21
P35G11	y	RCCW01	RCW01

ACTIVITY: ROTATE CW

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P23G22	n	RCW16	RCCW14
P24G01	n	RCW03	RCCW03
P24G11	n	RCW12	RCCW10
P25G05	n	RCW06	RCCW06
P25G06	n	RCW12	RCCW10
P26G05	n	RCW07	RCCW09
P26G16	n	RCW15	RCCW13
P27G03	n	RCW08	
P27G22	n	RCW03	RCCW03
P28G11	n	RCW05	RCCW05
P28G21	n	RCCW02	RCW02
P29G15	n	RCW13	RCCW11
P29G24	n	RCW05	RCCW05
P30G12	n	RCW05	RCCW05
P30G13	n	RCW26	
P31G01	n	NG	
P31G16	n	RCW02	RCCW02
P32G22	y	RCW13	RCCW11
P32G25	y	RCW13	RCCW11
P33G20	n	RCW01	RCCW01
P33G22	n	RCW04	RCCW04
P34G01	n	RCW13	RCCW11
P34G11	n	RCW12	RCCW10

ACTIVITY: ROTATE CCW

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P35G23	y	RCCW01	RCW01
P36G01	n	RCCW10	RCW12
P36G25	n	RCCW16	RCW19
P37G06	n	RCCW11	RCW13
P37G21	n	RCCW13	RCW15
P38G06	n	RCCW16	RCW19
P38G07	n	RCCW10	RCW12
P39G04	y	RCCW01	RCW01
P39G07	y	RCCW01	RCW01
P40G01	y	RCCW16	RCW19
P40G21	y	RCCW16	RCW19
P41G11	y	RCCW12	RCW14
P41G20	y	RCCW12	RCW14
P42G14	n	RCCW10	RCW12
P42G15	n	RCCW17	RCW20
P43G06	n	RCCW13	RCW15
P43G21	n	RCCW10	RCW12
P44G11	y	RCCW08	RCW11
P44G20	y	RCCW08	RCW11

ACTIVITY: ROTATE CW

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P35G05	y	RCW01	RCCW01
P35G06	y	RCW01	RCCW01
P36G05	n	RCW12	RCCW10
P36G16	n	RCW19	RCCW16
P37G03	y	RCW15	RCCW13
P37G22	y	RCW15	RCCW13
P38G11	n	RCW19	RCCW16
P38G21	n	RCW12	RCCW10
P39G15	y	RCW01	RCCW01
P39G24	y	RCW01	RCCW01
P40G12	n	RCW19	RCCW16
P40G13	n	RCW27	
P41G01	n	RCW14	RCCW12
P41G16	n	RCW29	
P42G01	n	RCW15	RCCW13
P42G11	n	RCW20	RCCW17
P43G03	y	RCW19	RCCW16
P43G22	y	RCW19	RCCW16
P44G01	n	RCW14	RCCW12
P44G16	n	RCW11	RCCW08

Table 28 : Translate down/up activity for the phone and the sphere

ACTIVITY: TRANSLATE DOWN

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P01G04	n	TD25	TU07
P01G21	n	TD20	TU24
P02G07	n	TD19	
P02G11	n	TD08	TU10
P03G05	y	TD07	TU09
P03G09	y	TD07	TU09
P04G09	y	TD08	TU10
P04G20	y	TD08	TU10
P05G03	n	TD11	
P05G21	n	TD05	TU06
P06G15	y	TD09	TU13
P06G18	y	TD09	TU13
P07G07	y	TD08	TU10
P07G17	y	TD08	TU10
P08G03	n	TD05	TU06
P08G08	n	TD14	
P09G08	y	TD07	TU09
P09G25	y	TD07	TU09
P10G09	n	TD06	TU08
P10G18	n	TD05	TU06
P11G04	n	TD07	TU09
P11G21	n	TD11	
P12G07	y	TD02	TU02
P12G11	y	TD02	TU02
P13G03	n	TD08	TU10
P13G21	n	TD07	TU09
P14G05	n	TD07	TU09
P14G09	n	TD12	
P15G09	n	TD11	
P15G20	n	TD10	TU14
P16G15	n	TD11	
P16G18	n	TD04	TU05
P17G07	n	TD15	
P17G17	n	TD13	
P18G03	y	TD02	TU02
P18G08	y	TD02	TU02

ACTIVITY: TRANSLATE UP

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P11G19	n	TU01	
P44G19	n	TU01	
P27G01	n	TU02	
P01G09	y	TU24	TD20
P01G19	y	TU24	TD20
P11G09	n	TU03	
P06G11	y	TU13	
P06G24	y	TU13	
P07G01	y	TU10	
P07G10	y	TU10	
P13G14	n	TU04	
P19G22	n	TU04	
P30G08	n	TU04	
P16G24	n	TU05	
P21G19	n	TU05	
P08G19	n	TU06	
P18G19	n	TU06	
P04G03	n	TU07	
P09G22	n	TU08	
P10G08	n	TU08	
P13G08	n	TU08	
P14G10	n	TU08	
P18G10	n	TU08	
P25G07	n	TU08	
P12G17	y	TU03	
P12G21	y	TU03	
P31G19	n	TU08	
P03G10	n	TU09	
P21G09	n	TU09	
P03G23	n	TU10	
P04G07	n	TU10	
P26G11	y	TU10	
P26G24	y	TU10	
P10G05	n	TU10	
P24G23	n	TU10	
P29G22	y	TU08	

ACTIVITY: TRANSLATE DOWN

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P19G08	n	TD10	TU14
P19G25	n	TD11	
P20G09	n	TD11	
P20G18	n	TD15	
P21G04	y	TD07	TU09
P21G21	y	TD07	TU09
P22G07	n	TD11	
P22G11	n	TD26	TU25
P23G03	n	TD11	
P23G21	n	TD18	
P24G05	n	TD26	TU25
P24G09	n	TD01	TU01
P25G09	y	TD07	TU09
P25G20	y	TD07	TU09
P26G15	y	TD08	TU10
P26G18	y	TD08	TU10
P27G07	y	TD26	TU25
P27G17	y	TD26	TU25
P28G03	n	TD21	
P28G08	n	TD02	TU02
P29G08	y	TD07	TU09
P29G25	y	TD07	TU09
P30G09	n	TD03	TU04
P30G18	n	TD04	TU05
P31G04	y	TD07	TU09
P31G21	y	TD07	TU09
P32G07	n	TD02	TU02
P32G11	n	TD01	TU01
P33G03	n	TD04	TU05
P33G21	n	TD26	TU25
P34G05	n	TD16	
P34G09	n	TD11	
P35G09	y	TD22	
P35G20	y	TD22	
P36G15	y	TD20	TU24
P36G18	y	TD20	TU24
P37G07	y	TD07	TU09
P37G17	y	TD07	TU09

ACTIVITY: TRANSLATE UP

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P29G23	y	TU08	
P44G09	n	TU10	
P09G23	n	TU11	
P05G08	n	TU12	
P31G09	n	TU12	
P32G17	y	TU02	
P32G21	y	TU02	
P15G07	n	TU14	
P19G23	n	TU14	
P05G14	n	TU15	TD11
P08G10	n	TU15	TD11
P15G03	n	TU15	TD11
P16G11	n	TU15	TD11
P22G17	n	TU15	TD11
P34G10	n	TU15	TD11
P38G10	n	TU15	TD11
P40G08	n	TU15	TD11
P43G10	n	TU15	TD11
P17G01	n	TU16	TD12
P20G08	n	TU16	TD12
P23G14	n	TU16	TD12
P25G03	n	TU16	TD12
P02G17	n	TU17	
P17G10	n	TU18	TD15
P20G05	n	TU18	TD15
P22G21	n	TU18	TD15
P38G19	n	TU18	TD15
P34G23	n	TU19	TD16
P28G10	n	TU2	
P02G21	n	TU20	TD18
P14G23	n	TU20	TD18
P35G03	y	TU03	
P35G07	y	TU03	
P33G14	n	TU24	TD20
P36G11	y	TU24	TD20
P36G24	y	TU24	TD20
P40G05	n	TU24	TD20
P27G10	n	TU25	

ACTIVITY: TRANSLATE DOWN

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P38G03	n	TD15	
P38G08	n	TD11	
P39G08	y	TD23	
P39G25	y	TD23	
P40G09	n	TD11	
P40G18	n	TD17	
P41G04	n	TD26	TU25
P41G21	n	TD10	TU14
P42G05	y	TD26	TU25
P42G09	y	TD26	TU25
P43G07	n	TD11	
P43G17	n	TD24	
P44G04	n	TD08	TU10
P44G21	n	TD01	TU01

ACTIVITY: TRANSLATE UP

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P33G08	n	TU25	
P39G22	y	TU31	TD23
P39G23	y	TU31	TD23
P41G09	y	TU25	
P41G19	y	TU25	
P37G10	n	TU26	
P23G08	n	TU27	
P28G19	n	TU28	TD21
P24G10	n	TU29	
P30G05	n	TU29	
P37G01	n	TU31	TD23
P42G10	y	TU25	
P42G23	y	TU25	
P43G01	n	TU32	TD24

Table 29 : Translate left/right activity for the phone and the sphere

ACTIVITY: TRANSLATE LEFT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P01G02	y	TL11	TR11
P01G13	y	TL11	TR11
P02G02	y	TL01	TR01
P02G24	y	TL01	TR01
P03G19	y	TL06	TR06
P03G25	y	TL06	TR06
P04G10		TL01	TR01
P05G06	n	TL05	TR05
P05G19	n	TL17	TR17
P06G13	y	TL06	TR06
P06G23	y	TL06	TR06

ACTIVITY: TRANSLATE RIGHT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P01G03	n	TR06	TL06
P01G17	n	TR04	TL04
P02G03	y	TR01	TL01
P02G23	y	TR01	TL01
P03G13	n	TR01	TL01
P03G18	n	TR06	TL06
P04G04	n	TR06	TL06
P04G21	n	TR01	TL01
P05G04	n	TR17	TL17
P05G25	n	TR05	TL05
P06G04	y	TR06	TL06

ACTIVITY: TRANSLATE LEFT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P07G18	y	TL01	TR01
P07G19	y	TL01	TR01
P08G02	n	TL04	TR04
P08G23	n	TL18	TR18
P09G05	n	TL09	TR09
P09G17	n	TL06	TR06
P10G07	n	TL17	TR17
P10G11	n	TL11	TR11
P11G03	n	TR09	TL09
P11G13	n	TL02	TR02
P12G02	n	TL02	TR02
P12G24	n	TL03	TR03
P13G06	n	TL09	TR09
P13G19	n	TL10	TR10
P14G19	n	TL09	TR09
P14G25	n	TL19	
P15G10	n	TL17	TR17
P15G22	n	TL08	TR08
P16G13	n	TL17	TR17
P16G23	n	TL12	TR12
P17G18	n	TL17	TR17
P17G19	n	TL06	TR06
P18G02	n	TL07	TR07
P18G23	n	TL23	
P19G05	n	TL17	TR17
P19G17	n	TL06	TR06
P20G07	n	TL17	TR17
P20G11	n	TL20	TR19
P21G03	y	TR11	TL11
P21G13	y	TL11	TR11
P22G02	y	TL11	TR11
P22G24	y	TL11	TR11
P23G06	n	TL22	TR20
P23G19	n	TL21	
P24G19	n	TL12	TR12
P24G25	n	TL01	TR01
P25G10	y	TL06	TR06
P25G22	y	TL06	TR06

ACTIVITY: TRANSLATE RIGHT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P06G06	y	TR06	TL06
P07G13	y	TR01	TL01
P07G23	y	TR01	TL01
P08G12	n	TR04	TL04
P08G15	n	TR18	TL18
P09G10	y	TR09	TL09
P09G21	y	TR09	TL09
P10G10	n	TR04	TL04
P10G19	n	TR11	TL11
P11G02	n	TL09	TR09
P11G17	n	TR21	
P12G03	n	TR07	TL07
P12G23	n	TR03	TL03
P13G04	n	TR10	TL10
P13G25	n	TR09	TL09
P14G13	y	TR09	TL09
P14G18	y	TR09	TL09
P15G04	n	TR17	TL17
P15G21	n	TR08	TL08
P16G04	n	TR15	TL15
P16G06	n	TR18	TL18
P17G13	n	TR17	TL17
P17G23	n	TR06	TL06
P18G12	y	TR02	TL02
P18G15	y	TR02	TL02
P19G10	n	TR14	TL14
P19G21	n	TR10	TL10
P20G10		TR19	TL20
P21G02	n	TL02	TR2
P21G17	n	TR03	TL03
P22G03	y	TR11	TL11
P22G23	y	TR11	TL11
P23G04	n	TR17	TL17
P23G25	n	TR09	TL09
P24G13	n	TR15	TL15
P24G18	n	TR12	TL12
P25G04	y	TR06	TL06
P25G21	y	TR06	TL06

ACTIVITY: TRANSLATE LEFT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P26G13	y	TL01	TR01
P26G23	y	TL01	TR01
P27G18	y	TL15	TR15
P27G19	y	TL15	TR15
P28G02	n	TL09	TR09
P28G23	n	TL07	TR07
P29G05	n	TL21	
P29G17	n	TL06	TR06
P30G07	n	TL17	TR17
P30G11	n	TL03	TR03
P31G03	n	TL06	TR06
P31G13	n	TL01	TR01
P32G02	y	TL02	TR02
P32G24	y	TL02	TR02
P33G06	n	TL06	TR06
P33G19	n	TL13	TR13
P34G19	y	TL16	TR16
P34G25	y	TL16	TR16
P35G10	y	TL03	TR03
P35G22	y	TL03	TR03
P36G13	y	TL11	TR11
P36G23	y	TL11	TR11
P37G18	y	TL01	TR01
P37G19	y	TL01	TR01
P38G02	n	TL20	TR19
P38G23	n	TL17	TR17
P39G05	y	TL09	TR09
P39G17	y	TL09	TR09
P40G07	n	TL18	TR18
P40G11	n	TL17	TR17
P41G03	y	TR14	TL14
P41G13	y	TL14	TR14
P42G19	y	TL15	TR15
P42G25	y	TL15	TR15
P43G18	n	TL22	TR20
P43G19	n	TL17	TR17
P44G03	y	TR01	TL01
P44G13	y	TL01	TR01

ACTIVITY: TRANSLATE RIGHT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P26G04	y	TR01	TL01
P26G06	y	TR01	TL01
P27G13	y	TR15	TL15
P27G23	y	TR15	TL15
P28G12	y	TR07	TL07
P28G15	y	TR07	TL07
P29G10	y	TR06	TL06
P29G21	y	TR06	TL06
P30G10	n	TR01	TL01
P30G19	n	TR17	TL17
P31G02	n	TR06	TL06
P31G17	n	TR01	TL01
P32G03	y	TR02	TL02
P32G23	y	TR02	TL02
P33G04	n	TR13	TL13
P33G25	n	TR15	TL15
P34G13	n	TR17	TL17
P34G18	n	TR16	TL16
P35G04	y	TR03	TL03
P35G21	y	TR03	TL03
P36G04	y	TR11	TL11
P36G06	y	TR11	TL11
P37G13	y	TR01	TL01
P37G23	y	TR01	TL01
P38G12	n	TR19	TL20
P38G15	n	TR18	TL18
P39G10	y	TR09	TL09
P39G21	y	TR09	TL09
P40G10	y	TR17	TL17
P40G19	y	TR17	TL17
P41G02	n	TL14	TR14
P41G17	n	TR15	TL15
P42G13	y	TR15	TL15
P42G18	y	TR15	TL15
P43G13	n	TR20	TL22
P43G23	n	TR17	TL17
P44G02	n	TL01	TR01
P44G17	n	TR11	TL11

Table 30 : Zoom in/out activity for the phone and the sphere

ACTIVITY: ZOOM IN

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P01G12	n	ZI10	
P01G14	n	ZI37	
P02G04	n	ZI20	ZO21
P02G20	n	ZI21	
P03G04	n	ZI01	ZO01
P03G17	n	ZI03	
P03G41		Zoom08	
P03G41		ZI03	
P04G17	y	ZI01	ZO01
P04G19	y	ZI01	ZO01
P05G15	n	ZI17	ZO17
P05G23	n	ZI16	ZO16
P06G07	y	ZI35	ZO34
P06G09	y	ZI35	ZO34
P07G08	n	ZI12	
P07G25	n	ZI21	
P08G04	n	ZI11	ZO11
P08G09	n	ZI18	ZO18
P09G11	y	ZI29	ZO28
P09G12	y	ZI29	ZO28
P10G02	n	ZI21	
P10G22	n	ZI22	
P11G12	n	ZI04	ZO03
P11G14	n	ZI08	ZO08
P12G04	y	ZI07	ZO07
P12G20	y	ZI07	ZO07
P13G15	n	ZI31	ZO31
P13G23	n	ZI30	ZO29
P14G04	n	ZI16	ZO16
P14G17	n	ZI19	ZO20
P15G17	n	ZI35	ZO34
P15G19	n	ZI17	ZO17
P16G07	n	ZI23	
P16G09	n	ZI19	ZO20

ACTIVITY: ZOOM OUT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P01G05	y	ZO29	ZI30
P01G10	y	ZO29	ZI30
P02G15	n	ZO21	ZI20
P02G19	n	ZO16	ZI16
P03G21	y	ZO01	ZI01
P03G22	y	ZO01	ZI01
P04G02		ZO18	ZI18
P05G10	n	ZO17	ZI17
P05G24	n	ZO16	ZI16
P06G10	n	ZO12	
P06G20	n	ZO32	ZI34
P07G04	y	ZO18	ZI18
P07G20	y	ZO18	ZI18
P08G05	n	ZO11	ZI11
P08G25	n	ZO19	
P09G06	y	ZO29	ZI30
P09G09	y	ZO29	ZI30
P10G06	n	ZO16	ZI16
P10G15	n	ZO17	ZI17
P11G05	n	ZO29	ZI30
P11G10	n	ZO09	
P12G15	y	ZO07	ZI07
P12G19	y	ZO07	ZI07
P13G10	n	ZO31	ZI31
P13G24	n	ZO29	ZI30
P14G21	n	ZO29	ZI30
P14G22	n	ZO20	ZI19
P15G02	n	ZO17	ZI17
P15G25	n	ZO34	ZI35
P16G10	n	ZO20	ZI19
P16G20	n	ZO17	ZI17
P17G04	n	ZO17	ZI17
P17G20	n	ZO22	
P18G05	n	ZO01	ZI01

ACTIVITY: ZOOM IN

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P17G08	n	ZI17	ZO17
P17G25	n	ZI23	
P18G04	y	ZI01	ZO01
P18G09	y	ZI01	ZO01
P19G11	n	ZI10	
P19G12	n	Eliminated	
P20G02		ZI27	
P21G12	y	ZI26	
P21G14	y	ZI26	
P22G04	n	ZI17	ZO17
P22G20	n	ZI16	ZO16
P23G15	y	ZI13	ZO13
P23G23	y	ZI13	ZO13
P24G04	y	ZI16	ZO16
P24G17	y	ZI16	ZO16
P25G17	n	ZI25	
P25G19	n	ZI17	ZO17
P26G07	y	ZI01	ZO01
P26G09	y	ZI01	ZO01
P27G08	n	ZI32	
P27G25	n	ZI28	ZO26
P28G04	y	ZI34	ZO32
P28G09	y	ZI34	ZO32
P29G11	n	ZI17	ZO17
P29G12	n	ZI29	ZO28
P30G02	n	ZI33	
P30G22	n	ZI31	ZO31
P31G12	y	ZI01	ZO01
P31G14	y	ZI01	ZO01
P32G04	n	ZI05	ZO04
P32G20	n	ZI19	ZO20
P33G15	n	ZI29	ZO28
P33G23	n	ZI30	ZO29
P34G04	y	ZI08	ZO08
P34G17	y	ZI08	ZO08
P35G17	y	ZI01	ZO01
P35G19	y	ZI01	ZO01

ACTIVITY: ZOOM OUT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P18G25	n	ZO29	ZI30
P19G06	n	ZO29	ZI30
P19G09	n	ZO18	ZI18
P20G06	n	ZO28	ZI29
P20G15	n	ZO17	ZI17
P21G05	y	ZO13	ZI13
P21G10	y	ZO13	ZI13
P22G15	n	ZO17	ZI17
P22G19	n	ZO16	ZI16
P23G10	y	ZO29	ZI30
P23G24	y	ZO29	ZI30
P24G21	n	ZO23	
P24G22	n	ZO17	ZI17
P25G02	y	ZO29	ZI30
P25G25	y	ZO29	ZI30
P26G10	y	ZO01	ZI01
P26G20	y	ZO01	ZI01
P27G04	n	ZO13	ZI13
P27G20	n	ZO27	
P28G05	y	ZO32	ZI34
P28G25	y	ZO32	ZI34
P29G06	n	ZO29	ZI30
P29G09	n	ZO18	ZI18
P30G06	n	ZO29	ZI30
P30G15	n	ZO17	ZI17
P31G05	y	ZO32	ZI34
P31G10	y	ZO32	ZI34
P32G15	y	ZO20	ZI19
P32G19	y	ZO20	ZI19
P33G10	n	ZO25	
P33G24	n	ZO29	ZI30
P34G21	y	ZO04	ZI05
P34G22	y	ZO04	ZI05
P35G02	y	ZO18	ZI18
P35G25	y	ZO18	ZI18
P36G10	y	ZO14	ZI14
P36G20	y	ZO14	ZI14

ACTIVITY: ZOOM IN

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P36G07	y	ZI14	ZO14
P36G09	y	ZI14	ZO14
P37G08	n	ZI15	ZO15
P37G25	n	ZI24	
P38G04	n	ZI36	ZO35
P38G09	n	ZI17	ZO17
P39G11	y	ZI30	ZO29
P39G12	y	ZI30	ZO29
P40G02	y	ZI01	ZO01
P40G22	y	ZI01	ZO01
P41G12	y	ZI30	ZO29
P41G14	y	ZI30	ZO29
P42G04	y	ZI02	ZO02
P42G17	y	ZI02	ZO02
P43G08	n	ZI06	ZO05
P43G25	n	ZI09	ZO10
P44G12	y	ZI14	ZO14
P44G14	y	ZI14	ZO14

ACTIVITY: ZOOM OUT

Participant and gesture code	Same gesture performed for phone and sphere	Unique number	Equivalent to
P37G04	n	ZO15	ZI15
P37G20	n	ZO01	ZI01
P38G05	n	ZO35	ZI36
P38G25	n	ZO17	ZI17
P39G06	n	ZO06	
P39G09	n	ZO29	ZI30
P40G06	y	ZO01	ZI01
P40G15	y	ZO01	ZI01
P41G05	n	ZO33	
P41G10	n	ZO30	
P42G21	y	ZO02	ZI02
P42G22	y	ZO02	ZI02
P43G04	n	ZO05	ZI06
P43G20	n	ZO03	ZI04
P44G05	y	ZO14	ZI14
P44G10	y	ZO14	ZI14

Appendix H- Evaluation

Participant demographics, data collected form each participant, summary of data and questionnaire they had to complete are provided in this appendix.

H 1 Participant demographics

Participant no	Gender	Age	Occupation	University	Previous degree	If you used CAD in the past which one did you use?	Years of experience in current occupation	left or right handed	Used AR/vR in the past?	No of years	VR performed first during evaluation
1	M	31	Mechanical Engineer	Strathclyde	PHD	Solidworks	3	right	no	n/a	y
2	F	35	Researcher - organisational management	Strathclyde	PHD	No	4	right	no	n/a	n
3	F	46	Researcher - organisational management	Strathclyde	BSc	No	15	right	no	n/a	n
4	F	27	Marketing manager	GCU	BA(Hons) Fashion Business	Kaleido Style	4	right	Oculus rift	briefly in an event	y
5	M	28	Mechanical Engineer	Strathlcyde	MSc	Solidworks	1	left	no	n/a	y
6	M	34	Teaching Associate - cost forecasting	Strathclyde	MSc	Solidworks	3	right	no	n/a	y
7	F	31	Free-lance architect	Strathclyde	MARCH (Master in Architecture)	Autocad, Revit	3	left	no	n/a	n
8	M	28	Electrical Engineer	Strathclyde	EngD	Creo	1	right	Vive and Rift	2	y
9	F	34	Electrical Engineer	University of Novi Sad	Master	no	5	right	no	n/a	n
10	F	31	Architect	IUAV - Venice University of Architecture	Master	Autocad, Revit	5	right	Oculus rift	briefly in an event	n

H 2 Participant data

Results for each participant are given. When more than one gesture was performed participants were asked to choose their preferred gestures. The chosen gesture is bolded in the table.

H 2.1 Participant 1

Table 31 : Participant 1- VR results

VR	**Translate left/right**				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**				
	TLR1 (TL01.2/TR01.2)	TLR2 (TL01.3/TR01.3)	TLR3 (TL01.1/TR01.1)	TLR4 (TL03.1/TR03.1)	TUD1 (TU01.6/TD01.1)	**TUD2 (TU01.1/TD01.5)**	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	R1 (RCW01.1/RCCW01.1)	R2 (RCW01.2/RCCW01.2)	R3 (RCW01.3/RCCW01.3)	**R4 (RCW02.1/RCCW02.1)**	**Z1 (ZO01.1/ZI01.1)**	Z2 (ZO04.1/ZI02.1)	Z3 (ZO05.1)	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	6	6	6	5	6	6	6	5	6	6	2	7	6	5	4	4	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	6	6	7	6	6	6	5	6	6	2	7	6	6	6	6	7
3. Was the gesture resulted in the action you expected?	7	6	7	7	6	6	6	5	6	6	2	6	7	7	6	6	7
4. How difficult is it to perform the gesture (considering technology)?	6	6	3	6	5	6	6	5	7	3	1	1	6	6	5	5	7
5. Any other comments:	rotating a palm to push a specific way would be good				sensitivity too low	better than palm down (more intuitive due to gravity)		sensitivity issue again					slight lag				Fiddly. Would be good to have the single tap for entire area, second tap for the surface/entity you want

Table 32 : Participant 1 - Abstract guided results

Abstract – guided	**Translate up**						**Translate down**				**Translate left**					**Translate right**					**Extrude up**			**Extrude down**		
	TU08	TU10	TU15	TU16	TU20	TU24	**TD07**	TD08	TD11	TD26	TL01	**TL06**	TL17	TL09	TL11	TR01	**TR06**	TR017	TR09	TR11	**EU04**	EU15	EU16	**ED02**	ED14	ED16
1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)	7	5	5	5	4	5	7	6	5	2	6	7	5	7	7	6	7	5	7	7	7	4	7	7	4	4
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	5	5	4	7	7	7	5	6	7	7	5	5	6	7	7	5	5	6	5	6	7	5	6	6
3. Any other comments:																					because it gives you a distance			others can be mixed up with TLR		

Table 33 : Participant 1 – Abstract guided results (continued)

Abstract – guided (continuation)	**Extrude cut**		**Extrude cut shallower**		**Rotate clockwise**				**Rotate counter clockwise**				**Zoom in**				**Zoom out**					**Select**		**Deselec t**	
	EC12	**EC13**	**ECS05**	ECS20	**RCW01**	RCW12	RCW13	RCW19	**RCCW01**	RCCW10	RCCW11	RCCW16	**ZI01**	ZI16	ZI17	ZI30	**ZO01**	ZO16	ZO17	ZO18	ZO29	S10	**S11**	D10	**D11**
1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)	2	4	2	2	7	6	6	5	7	6	6	5	6	5	2	2	6	5	2	2	2	2	6	2	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	5	5	7	5	5	5	7	5	5	5	6	5	5	7	6	5	5	6	7	6	6	6	6
3. Any other comments:		ideally it would be a different gesture	ideally it would be a different gesture																						

Table 34 : Participant 1 - Abstract free results

Abstract - free	**Bend**	**Draw**	**Extrude cut**						**Extrude**					**Fillet**		**Join**		**Multiply/Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19		ExtC05	ExtC07	ExtC08	**ExtC10**	ExtC12	Ext13	**Ext15**	Ext17	Ext20	Ext22	Fil05	**Fil16**	Join01	**Join06**	**MulPat06**	MulPat07	Scul01	Scul02	**Scul05**	Select01	Slice03	**Und01**	Und02	Und08	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)	7	7		5	6	6	6	2	6	7	2	2	3	4	5	6	7	6	3	2	2	3	6	5	6	5	4	2	5	5
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	5	7		6	6	6	6	5	5	5	5	6	6	6	6	5	5	5	5	5	5	5	6	6	6	6	5	4	5	5
3. Any other comments:																						ideally it would be a different gesture		there is probably a better way to do it	ideally something else					

H 2.2 Participant 2

Table 35 : Participant 2 - VR results

VR	**Translate left/right**				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**				
	TLR1 (TL01.2/TR01.2)	TLR2 (TL01.3/TR01.3)	TLR3 (TL01.1/TR01.1)	TLR4 (TL03.1/TR03.1)	**TUD1 (TU01.6/TD01.1)**	TUD2 (TU01.1/TD01.5)	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	**R1 (RCW01.1/RCCW01.1)**	R2 (RCW01.2/RCCW01.2)	R3 (RCW01.3/RCCW01.3)	R4 (RCW02.1/RCCW02.1)	Z1 (ZO01.1/ZI01.1)	Z2 (ZO04.1/ZI02.1)	**Z3 (ZO05.1)**	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	6	1	5	6	6	6	6	6	7	7	3	7	3	5	7	3	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	1	5	7	7	6	7	6	7	7	5	7	3	5	7	5	7
3. Was the gesture resulted in the action you expected?	7	1	6	6	7	2	7	2	7	2	1	1	1	5	7	2	7
4. How difficult is it to perform the gesture (considering technology)?	6	1	6	1	7	1	7	3	7	3	2	1	2	3	6	1	5
5. Any other comments:																	would be nice to change colour to acknowledge

Table 36 : Participant 2 – Abstract guided results

Abstract - guided	**Translate up**						**Translate down**				**Translate left**					**Translate right**					**Extrude up**			**Extrude down**		
	TU08	TU10	**TU15**	TU16	TU20	TU24	TD07	TD08	**TD11**	TD26	**TL01**	TL06	TL17	TL09	TL11	**TR01**	TR06	TR017	TR09	TR11	**EU04**	EU15		**ED02**	ED14	ED16
1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)	6	2	7	7	6	3	5	3	6	2	5	2	5	5	5	6	3	5	3	3	3	2		1	2	2
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7		7	7	2
3. Any other comments:	2 hand prefe rred					Unle ss it's a pipe					Probab ly not full hand										hold hand palm up			(chosen but not preferre d)	wo uld mo ve	

Table 37 : Participant 2 - Abstract guided results (continued)

Abstract - guided	**Extrude cut**		**Extrude cut shallower**		**Rotate clockwise**				**Rotate counter clockwise**				**Zoom in**				**Zoom out**					**Select**		**Deselect**	
	EC12	**EC13**	**ECS05**	ECS20	RCW01	**RCW12**	RCW13	RCW19	RCCW01	**RCCW10**	RCCW11	RCCW16	ZI01	**ZI16**	ZI17	ZI30	ZO01	**ZO16**	ZO17	ZO18	ZO29	S10	**S11**	D10	**D11**
1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)	2	3	6	2	5	7	5	5	5	7	5	5	1	2	2	2	1	2	2	2	2	7	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:		(chosen but not preferred)						if it was heavier																	
		1	1			1				1				1				1					1		1

Table 38 : Participant 2 – Abstract free results

Abstract - free	**Bend**	**Draw**	**Extrude cut**						**Extrude**					**Fillet**		**Join**		**Multiply/Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19	ExtC01		**ExtC07**	ExtC08	ExtC10	ExtC12	Ext13	**Ext15**	Ext17	Ext20	Ext22	**Fil05**	Fil16	**Join01**	Join06	MulPat06	**MulPat07**	Scul01	**Scul02**	Scul05	Select01	Slice03	Und01	Und02	**Und08**	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)	7	7	1		3	7	3	3	2	7	5	2	5	5	5	7	6	5	6	1	2	2	7	6	6	3	7	7	3	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7		7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:														woul d hold it too																

H 2.3 Participant 3

Table 39 : Participant 3 - VR results

VR	**Translate left/right**				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**				
	TLR1 (TL01.2/TR01.2)	TLR2 (TL01.3/TR01.3)	**TLR3 (TL01.1/TR01.1)**	TLR4 (TL03.1/TR03.1)	**TUD1 (TU01.6/TD01.1)**	**TUD2 (TU01.1/TD01.5)**	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	R1 (RCW01.1/RCCW01.1)	R2 (RCW01.2/RCCW01.2)	R3 (RCW01.3/RCCW01.3)	**R4 (RCW02.1/RCCW02.1)**	**Z1 (ZO01.1/ZI01.1)**	Z2 (ZO04.1/ZI02.1)	Z3 (ZO05.1)	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	7	7	7	2	6	6	7	2	3	3	2	7	7	7	2	2	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	2	7	7	7	2	4	4	3	7	7	7	6	6	7
3. Was the gesture resulted in the action you expected?	7	7	7	1	7	7	7	2	6	6	4	7	7	7	6	6	7
4. How difficult is it to perform the gesture (considering technology)?	7	7	7	2	7	7	7	2	7	7	5	2	7	7	4	4	4
5. Any other comments:					yes for up	yes for down			too much work	too much work			scary				

Table 40 : Participant 3 - Abstract guided results

Abstract - guided	**Translate up**						**Translate down**				**Translate left**					**Translate right**					**Extrude up**			**Extrude down**		
	TU08	TU10	TU15	TU16	TU20	TU24	**TD07**	TD08	TD11	TD26	**TL01**	TL06	TL17	TL09	TL11	**TR01**	TR06	TR017	TR09	TR11	**EU04**	EU15	EU16	ED02	**ED14**	ED16
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	6	6	1	1	3	7	6	6	1	7	6	1	3	5	7	6	1	3	5	2	2	2	1	6	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	5	6	6	7	7	7	6	7	7	5	7	7	7	7	5	7	7	7	7	7	7	7	7
3. Any other comments:					unless it's a specific shape	depends on shape									depends on the shape (if a part of a smaller object then yes)					depends on the shape (if a part of a smaller object then yes)	wouldn't hold	unless it's already partly extruded				

Table 41 : Participant 3 – Abstract guided results (continued)

Abstract - guided	**Extrude cut**		**Extrude cut shallower**		**Rotate clockwise**				**Rotate counter clockwise**				**Zoom in**				**Zoom out**					**Select**		**Deselect**	
	EC12	**EC13**	ECS05	**ECS20**	**RCW01**	RCW12	RCW13	RCW19	**RCCW01**	RCCW10	RCCW11	RCCW16	ZI01	ZI16	ZI17	**ZI30**	ZO01	ZO16	ZO17	ZO18	**ZO29**	S10	**S11**	D10	**D11**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	6	7	6	7	7	2	1	1	7	2	1	1	6	5	7	7	6	5	7	6	7	6	7	6	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	5	5	5	7	5	5	5	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:			not hold			not two hands				not two hands															

Table 42 : Participant 3 - Abstract free results

Abstract - free	**Bend**	**Draw**	**Extrude cut**						**Extrude**					**Fillet**		**Join**		**Multiply /Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19		**ExtC05**	ExtC07	ExtC08	ExtC10	ExtC12	Ext13	Ext15	Ext17	Ext20	**Ext22**	**Fil05**	Fil16	**Join01**	Join06	**MulPat06**	MulPat07	**Scul01**	**Scul02**	Scul05	Select01	Slice03	**Und01**	Und02	Und08	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7		7	2	7	7	1	5	6	2	5	7	7	2	7	7	6	5	6	6	1	7	7	7	2	6	6	7	5
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7		7	7	7	7	7	7	7	6	7	7	7	5	7	7	5	5	7	7	7	7	7	7	7	6	7	7	7
3. Any other comments:					not use two han ds												depe nds on the shape	don't really like either									would hope you wouldn't have to hold the object			

H 2.4 Participant 4

Table 43 : Participant 4 - VR results

VR	**Translate left/right**				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**				
	TLR1 (TL01.2/TR01.2)	TLR2 (TL01.3/TR01.3)	TLR3 (TL01.1/TR01.1)	TLR4 (TL03.1/TR03.1)	TUD1 (TU01.6/TD01.1)	**TUD2 (TU01.1/TD01.5)**	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	R1 (RCW01.1/RCCW01.1)	R2 (RCW01.2/RCCW01.2)	R3 (RCW01.3/RCCW01.3)	**R4 (RCW02.1/RCCW02.1)**	**Z1 (ZO01.1/ZI01.1)**	Z2 (ZO04.1/ZI02.1)	Z3 (ZO05.1)	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	7	7	7	5	7	7	1	6	5	5	1	7	3	5	5	5	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	5	2	3	7	7	5	7	7	7
3. Was the gesture resulted in the action you expected?	7	7	7	7	7	7	5	7	5	5	3	7	1	3	5	5	7
4. How difficult is it to perform the gesture (considering technology)?	7	7	7	7	7	7	7	2	7	3	2	7	7	7	7	7	5
5. Any other comments:																	

Table 44 : Participant 4 – Abstract guided results

Abstract- guided	**Translate up**						**Translate down**				**Translate left**					**Translate right**					**Extrude up**			**Extrude down**		
	TU08	TU10	TU15	TU16	TU20	TU24	**TD07**	TD08	TD11	TD26	TL01	**TL06**	TL17	TL09	TL11	TR01	**TR06**	TR017	TR09	TR11	EU04	**EU15**	EU16	ED02	ED14	**ED16**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	2	5	5	1	2	7	2	6	1	6	6	5	5	3	6	6	5	5	3	7	7	1	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:																										

Table 45 : Participant 4 – Abstract guided results (continued)

Abstract - guided	**Extrude cut**		**Extrude cut shallower**		**Rotate clockwise**				**Rotate counter clockwise**				**Zoom in**				**Zoom out**					**Select**		**Deselect**	
	EC12	EC13	ECS05	**ECS20**	**RCW01**	RCW12	RCW13	RCW19	**RCCW01**	RCCW10	RCCW11	RCCW16	**ZI01**	ZI16	ZI17	ZI30	**ZO01**	ZO16	ZO17	ZO18	ZO29	S10	**S11**	D10	**D11**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	6	2	5	7	6	1	5	1	6	1	5	1	6	1	1	1	6	1	1	1	1	7	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	2	7	7	7	2	7	7	7	7	7	3	7	7	7	7	3	7	7	7	7
3. Any other comments:																									

Table 46 : Participant 4 - Abstract free results

Abstract - free	**Bend**	**Draw**	**Extrude cut**						**Extrude**					**Fillet**		**Join**		**Multiply/Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19		**ExtC05**	ExtC07	ExtC08	ExtC10	ExtC12	Ext13	Ext15	Ext17	Ext20	**Ext22**	**Fil05**	Fil16	Join01	**Join06**	**MulPat06**	MulPat07	Scul01	**Scul02**	Scul05	Select01	Slice03	**Und01**	Und02	Und08	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7		5	1	5	3	3	1	5	1	1	7	7	1	5	7	1	1	5	6	1	7	7	7	2	5	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7		7	7	7	7	3	7	7	7	7	7	7	7	7	7	1	1	7	7	1	7	7	7	7	7	7	7	7
3. Any other comments:																														

H 2.5 Participant 5

Table 47 : Participant 5 - VR results

VR	Translate left/right				Translate up/down				Rotate CW/CCW				Zoom in/out				
	TLR1 (TL01.2/TR01.2)	TLR2 (TL01.3/TR01.3)	**TLR3 (TL01.1/TR01.1)**	TLR4 (TL03.1/TR03.1)	TUD1 (TU01.6/TD01.1)	TUD2 (TU01.1/TD01.5)	**TUD3 (TU01.2/TD01.2)**	TUD4 (TU02.2/TD02.1)	R1 (RCW01.1/RCCW01.1)	R2 (RCW01.2/RCCW01.2)	R3 (RCW01.3/RCCW01.3)	**R4 (RCW02.1/RCCW02.1)**	**Z1 (ZO01.1/ZI01.1)**	Z2 (ZO04.1/ZI02.1)	Z3 (ZO05.1)	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	6	2	6	1	7	4	6	3	6	5	3	7	6	6	2	1	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	6	2	7	1	7	4	6	5	7	6	2	7	7	7	7	5	7
3. Was the gesture resulted in the action you expected?	6	7	7	1	7	7	7	4	7	6	5	7	7	7	4	4	7
4. How difficult is it to perform the gesture (considering technology)?	7	1	7	1	1	4	7	4	7	5	1	1	6	7	1	1	2
5. Any other comments:	With some distance you can push	Extremely easy	I like it			Yes for up, no for down		Probably one hand is enough	Better to not use both hands, unless necessry for precision		Better to use 1 hand		after some training ok		Hard to control	Even harder to control	Does not always work. Depth perception an issue/cannot tell at what depth it catches.

Table 48 : Participant 5 - Abstract guided results

Abstract - guided	**Translate up**						**Translate down**				**Translate left**					**Translate right**					**Extrude up**			**Extrude down**		
	TU08	TU10	TU15	**TU16**	TU20	TU24	**TD07**	TD08	TD11	TD26	TL01	**TL06**	TL17	TL09	TL11	TR01	**TR06**	TR017	TR09	TR11	EU04	**EU15**		ED02	ED14	**ED16**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	5	5	6	5	6	7	6	5	2	7	7	5	6	6	7	7	5	6	6	2	7		2	6	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	5	7	5	7	7	7	4	7	7	7	7	7	6	7	7	7	7	6	7	7	7		7	6	7
3. Any other comments:			Not two hands if not necessary	Woul dusually use it at 45 deg																	Would prefer using the grasping hand only					

Table 49 : Participant 5 - Abstract guided results (continued)

Abstract - guided	**Extrude cut**		**Extrude cut shallower**		**Rotate clockwise**				**Rotate counter clockwise**				**Zoom in**				**Zoom out**					**Select**		**Deselect**	
	EC12	EC13	ECS05	**ECS20**	**RCW01**	RCW12	RCW13	RCW19	**RCCW01**	RCCW10	RCCW11	RCCW16	ZI01	ZI16	ZI17	**ZI30**	ZO01	ZO16	ZO17	ZO18	**ZO29**	S10	**S11**	D10	**D11**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7	2	7	7	5	5	5	7	5	5	5	7	1	1	7	7	1	1	7	7	7	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	6	6	5	7	6	6	5	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:			Would prefer no holding																						

Table 50 : Participant 5 - Abstract free results

Abstract - free	**Bend**	**Draw**	**Extrude cut**						**Extrude**					**Fillet**		**Join**		**Multiply/Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19		**ExtC05**	ExtC07	ExtC08	ExtC10	ExtC12	Ext13	Ext15	Ext17	**Ext20**	Ext22	**Fil05**	Fil16	Join01	**Join06**	**MulPat06**	MulPat07	Scul01	Scul02	**Scul05**	Select01	Slice03	**Und01**	Und02	Und08	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7		7	1	5	1	1	1	1	5	7	7	7	2	7	7	7	6	2	2	6	7	7	2	1	2	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7		7	7	7	7	7	7	7	7	7	7	7	2	7	7	7	4	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:					No need to hold																									Too similar to zoom in. Better if unique.

H 2.6 Participant 6

Table 51 : Participant 6 - VR results

VR	**Translate left/right**				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**				
	TLR1 (TL01.2/TR01.2)	TLR2 (TL01.3/TR01.3)	TLR3 (TL01.1/TR01.1)	TLR4 (TL03.1/TR03.1)	**TUD1 (TU01.6/TD01.1)**	TUD2 (TU01.1/TD01.5)	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	R1 (RCW01.1/RCCW01.1)	R2 (RCW01.2/RCCW01.2)	R3 (RCW01.3/RCCW01.3)	**R4 (RCW02.1/RCCW02.1)**	Z1 (ZO01.1/ZI01.1)	Z2 (ZO04.1/ZI02.1)	**Z3 (ZO05.1)**	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	7	6	6	5	7	7	7	3	7	2	1	7	6	6	7	5	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	6	7	5	7	7	6	1	7	2	1	7	7	7	7	7	7
3. Was the gesture resulted in the action you expected?	7	7	7	7	6	6	7	1	7	4	3	7	7	7	7	7	6
4. How difficult is it to perform the gesture (considering technology)?	7	7	7	1	6	6	7	1	7	2	2	2	6	7	7	2	3
5. Any other comments:				two hands not ideal			physically tiring	not two hands					not both hands				tiny things would be hard to select

Table 52 : Participant 6 - Abstract guided results

Abstract - guided	Translate up						Translate down				Translate left					Translate right					Extrude up			Extrude down		
	TU08	TU10	TU15	TU16	TU20	TU24	**TD07**	TD08	TD11	TD26	TL01	**TL06**	TL17	TL09	TL11	TR01	**TR06**	TR017	TR09	TR11	EU04	**EU15**	EU16	ED02	ED14	**ED16**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	3	6	5	2	2	7	5	6	1	7	7	5	3	2	7	7	5	3	2	7	7	1	3	6	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	3	5	6	3	3	7	7	3	7	7	7	5	3	5	7	7	5	3	5	6	7	1	5	6	7
3. Any other comments:					if it was big				if it was big				not two hand s								both hands not easy			not two hand s		

Table 53 : Participant 6 - Abstract guided results (continued)

Abstract - guided	**Extr ude cut**		**Extrude cut shallower**		**Rotate clockwise**				**Rotate counter clockwise**				**Zoom in**				**Zoom out**					**Selec t**		**Desel ect**	
	EC12	EC13	ECS05	**ECS20**	**RCW01**	RCW12	RCW13	RCW19	**RCCW01**	RCCW10	RCCW11	RCCW16	**ZI01**	ZI16	ZI17	ZI30	**ZO01**	ZO16	ZO17	ZO18	ZO29	S10	**S11**	D10	**D11**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	5	3	7	7	5	3	3	7	5	3	3	7	6	3	7	7	6	3	6	7	6	7	6	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	5	5	7	7	5	3	3	7	5	3	3	7	6	3	7	7	6	3	6	7	6	7	6	7
3. Any other comments:			Not two hands			not two hands																			

Table 54 : Participant 6 - Abstract free results

Abstract - free	**Bend**	**Draw**	**Extrude cut**						**Extrude**					**Fillet**		**Join**		**Multiply/Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19		ExtC05	ExtC07	ExtC08	**ExtC10**	ExtC12	Ext13	Ext15	Ext17	Ext20	**Ext22**	Fil05	**Fil16**	**Join01**	Join06	MulPat06	**MulPat07**	Scul01	Scul02	**Scul05**	Select01	Slice03	Und01	**Und02**	Und08	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7		7	2	6	7	1	2	5	5	6	7	6	7	7	6	3	5	3	2	6	7	7	5	6	5	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7		7	2	6	7	1	2	5	5	6	7	6	7	7	6	6	5	6	5	6	7	7	5	6	5	7	7	7
3. Any other comments:																									would not want to flick it					

H 2.7 Participant 7

Table 55 : Participant 7 - VR results

VR	**Translate left/right**				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**				
	TLR1 (TL01.2/TR01.2)	**TLR2 (TL01.3/TR01.3)**	TLR3 (TL01.1/TR01.1)	TLR4 (TL03.1/TR03.1)	TUD1 (TU01.6/TD01.1)	**TUD2 (TU01.1/TD01.5)**	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	**R1 (RCW01.1/RCCW01.1)**	R2 (RCW01.2/RCCW01.2)	R3 (RCW01.3/RCCW01.3)	R4 (RCW02.1/RCCW02.1)	**Z1 (ZO01.1/ZI01.1)**	Z2 (ZO04.1/ZI02.1)	Z3 (ZO05.1)	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	6	7	2	4	5	7	4	3	6	7	5	3	6	5	5	3	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	6	7	7	5	6	7	6	4	6	6	6	5	6	6	4	4	7
3. Was the gesture resulted in the action you expected?	7	7	7	5	6	6	6	6	7	7	6	3	6	5	5	5	7
4. How difficult is it to perform the gesture (considering technology)?	4	7	7	1	5	6	7	5	7	3	6	2	7	6	5	4	3
5. Any other comments:	not moving well to the right																

Table 56 : Participant 7 - Abstract guided results

Abstract - guided	**Translate up**						**Translate down**				**Translate left**					**Translate right**					**Extrude up**			**Extrude down**		
	TU08	TU10	TU15	TU16	TU20	TU24	**TD07**	TD08	TD11	TD26	TL01	**TL06**	TL17	TL09	TL11	TR01	**TR06**	TR017	TR09	TR11	EU04	**EU15**	EU16	ED02	**ED14**	ED16
1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)	7	5	6	6	5	5	7	6	6	3	5	7	6	7	5	5	7	6	7	5	3	5	5	4	7	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:																					not two hands					

Table 57 : Participant 7 – Abstract guided results (continued)

Abstract - guided	Extrude cut		Extrude cut shallower		Rotate clockwise				Rotate counter clockwise				Zoom in				Zoom out					Select		Deselect	
	EC12	EC13	ECS05	**ECS20**	RCW01	RCW12	RCW13	**RCW19**	RCCW01	RCCW10	RCCW11	**RCCW16**	**ZI01**	ZI16	ZI17	ZI30	**ZO01**	ZO16	ZO17	ZO18	ZO29	S10	**S11**	D10	**D11**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	6	6	6	7	5	6	7	7	5	6	7	7	6	4	5	6	6	4	5	6	6	5	6	5	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:																									

Table 58 : Participant 7 - Abstract free results

Abstract - free	**Bend**	**Draw**	**Extrude cut**						**Extrude**					**Fillet**		**Join**		**Multiply/Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19		ExtC05	ExtC07	**ExtC08**	ExtC10	ExtC12	Ext13	Ext15	Ext17	Ext20	**Ext22**	Fil05	**Fil16**	**Join01**	Join06	**MulPat06**	MulPat07	Scul01	Scul02	**Scul05**	Select01	Slice03	Und01	Und02	**Und08**	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	6	5		6	5	6	4	2	2	3	5	6	7	5	6	6	5	6	5	3	4	5	5	6	6	5	7	6	7	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7		7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:																						none ideal								

H 2.8 Participant 8

Table 59 : Participant 8 - VR results

VR	**Translate left/right**				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**				
	TLR1 (TL01.2/TR01.2)	TLR2 (TL01.3/TR01.3)	TLR3 (TL01.1/TR01.1)	TLR4 (TL03.1/TR03.1)	TUD1 (TU01.6/TD01.1)	TUD2 (TU01.1/TD01.5)	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	R1 (RCW01.1/RCCW01.1)	R2 (RCW01.2/RCCW01.2)	R3 (RCW01.3/RCCW01.3)	R4 (RCW02.1/RCCW02.1)	Z1 (ZO01.1/ZI01.1)	Z2 (ZO04.1/ZI02.1)	Z3 (ZO05.1)	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	6	6	7	5	6	6	6	7	7	6	7	6	5	6	3	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	5	7	7	7	7	7	7	7	6	7	7	7	6	7
3. Was the gesture resulted in the action you expected?	7	7	7	4	7	7	6	7	7	7	7	7	7	7	3	7	7
4. How difficult is it to perform the gesture (considering technology)?	5	6	7	1	5	6	7	1	7	2	1	5	4	7	6	6	3
5. Any other comments:				Two handed thing not a good representation of moving something about													

Table 60 : Participant 8 - Abstract guided results

Abstract - guided	**Translate up**						**Translate down**				**Translate left**					**Translate right**					**Extrude up**			**Extrude down**		
	TU08	TU10	TU15	TU16	TU20	TU24	TD07	TD08	TD11	TD26	TL01	TL06	TL17	TL09	TL11	TR01	TR06	TR017	TR09	TR11	EU04	EU15	EU16	ED02	ED14	ED16
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	2	6	7	3	6	7	3	5	1	6	7	5	7	6	6	7	5	7	6	5	3	3	5	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	6	6	6	5	5	6	7	7	5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:																										

Table 61 : Participant 8 - Abstract guided results (continued)

Abstract - guided	Extrude cut		Extrude cut shallower		Rotate clockwise				Rotate counter clockwise				Zoom in				Zoom out					Select		Deselect	
	EC12	EC13	ECS05	ECS20	RCW01	RCW12	RCW13	RCW19	RCCW01	RCCW10	RCCW11	RCCW16	ZI01	ZI16	ZI17	ZI30	ZO01	ZO16	ZO17	ZO18	ZO29	S10	S11	D10	D11
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	6	6	2	6	7	7	7	6	7	7	7	6	5	7	6	2	5	7	6	2	2	7	6	7	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:																									

Table 62 : Participant 8 - Abstract free results

Abstract - free	Bend	Draw	Extrude cut						Extrude					Fillet		Join		Multiply/Pattern		Sculpt			Select	Slice	Undo			Zoom	Resize	Scale
	Bend02	Drw19		ExtC05	ExtC07	ExtC08	ExtC10	ExtC12	Ext13	Ext15	Ext17	Ext20	Ext22	Fil05	Fil16	Join01	Join06	MulPat06	MulPat07	Scul01	Scul02	Scul05	Select01	Slice03	Und01	Und02	Und08	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	5	7		5	3	3	2	1	3	6	5	5	7	6	7	5	6	5	6	1	2	1	6	7	5	6	1	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7		7	7	7	7	7	7	7	7	7	7	7	7	7	7	5	6	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:							Prefer not holding																							

H 2.9 Participant 9

Table 63 : Participant 9 - VR results

VR	**Translate left/right**				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**				
	TLR1 (TL01.2/TR01.2)	**TLR2 (TL01.3/TR01.3)**	TLR3 (TL01.1/TR01.1)	TLR4 (TL03.1/TR03.1)	**TUD1 (TU01.6/TD01.1)**	TUD2 (TU01.1/TD01.5)	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	R1 (RCW01.1/RCCW01.1)	**R2 (RCW01.2/RCCW01.2)**	R3 (RCW01.3/RCCW01.3)	R4 (RCW02.1/RCCW02.1)	**Z1 (ZO01.1/ZI01.1)**	Z2 (ZO04.1/ZI02.1)	Z3 (ZO05.1)	Z4 (ZO04.2/ZI02.2)	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	4	6	5	6	7	6	6	6	6	7	5	3	4	4	2	1	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	7	7	7	1	7	7	7	7	7
3. Was the gesture resulted in the action you expected?	6	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
4. How difficult is it to perform the gesture (considering technology)?	5	3	7	1	6	6	6	1	7	3	1	5	4	4	2	1	
5. Any other comments:															Push yes, pull no		

Table 64 : Participant 9 – Abstract guided results

Abstract - guided	**Translate up**						**Translate down**				**Translate left**					**Translate right**					**Extrude up**			**Extrude down**		
	TU08	TU10	TU15	TU16	TU20	TU24	TD07	TD08	TD11	TD26	TL01	TL06	TL17	TL09	TL11	TR01	TR06	TR017	TR09	TR11	EU04	EU15	EU16	ED02	ED14	ED16
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	5	5	5	4	3	5	3	6	2	7	6	1	3	5	6	6	5	5	3	2	7	1	4	7	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	5	5	4	7	7	7	7	7	7	7	5	7	7	7	7	7	7	7	7	7	1	7	7	7
3. Any other comments:																										

Table 65 : Participant 9 - Abstract guided results (continued)

Abstract - guided	Extrude cut		Extrude cut shallower		Rotate clockwise				Rotate counter clockwise				Zoom in				Zoom out					Select		Deselect	
	EC12	EC13	ECS05	ECS20	RCW01	RCW12	RCW13	RCW19	RCCW01	RCCW10	RCCW11	RCCW16	ZI01	ZI16	ZI17	ZI30	ZO01	ZO16	ZO17	ZO18	ZO29	S10	S11	D10	D11
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	6	6	6	7	7	2	3	3	7	2	1	1	7	4	3	3	7	4	3	3	3	6	7	6	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	5	3	3	7	5	5	5	6	5	5	7	6	5	5	6	7	7	7	7	7
3. Any other comments:																									

Table 66 : Participant 9 - Abstract free results

Abstract - free	**Bend**	**Draw**	**Extrude cut**						**Extrude**					**Fillet**		**Join**		**Multiply/Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19		ExtC05	ExtC07	**ExtC08**	ExtC10	ExtC12	Ext13	Ext15	Ext17	Ext20	**Ext22**	**Fil05**	Fil16	Join01	**Join06**	MulPat06	**MulPat07**	Scul01	Scul02	**Scul05**	Select01	Slice03	Und01	Und02	Und08	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7		6	5	6	4	2	5	6	5	6	7	7	5	6	6	5	5	3	2	6	7	7	5	6	5	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7		7	7	7	7	7	5	7	5	6	7	7	7	7	7	6	5	6	5	6	7	7	5	6	5	7	7	7
3. Any other comments:																														

H 2.10 Participant 10

Table 67 : Participant 10 - VR results

VR	Translate left/right				Translate up/down				Rotate CW/CCW				Zoom in/out				
	TLR1 (TL01.2/TR01.2)	TLR2 (TL01.3/TR01.3)	TLR3 (TL01.1/TR01.1)	TLR4 (TL03.1/TR03.1)	**TUD1 (TU01.6/TD01.1)**	TUD2 (TU01.1/TD01.5)	TUD3 (TU01.2/TD01.2)	TUD4 (TU02.2/TD02.1)	R1 (RCW01.1/RCCW01.1)	**R2 (RCW01.2/RCCW01.2)**	**R3 (RCW01.3/RCCW01.3)**	R4 (RCW02.1/RCCW02.1)	Z1 (ZO01.1/ZI01.1)	Z2 (ZO04.1/ZI02.1)	**Z3 (ZO05.1)**	**Z4 (ZO04.2/ZI02.2)**	S/D (D01.1/S01.1)
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	7	7	7	7	7	7	7	7	6	7	7	7	2	1	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	7	7	7	7	7	2	1	7	7	7
3. Was the gesture resulted in the action you expected?	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
4. How difficult is it to perform the gesture (considering technology)?	7	7	7	7	7	7	7	7	7	3	2	4	4	4	2	2	5

Table 68 : Participant 10 - Abstract guided results

Abstract - guided	Translate up						Translate down				Translate left					Translate right					Extrude up			Extrude down		
	TU08	**TU10**	TU15	TU16	TU20	TU24	**TD07**	**TD08**	TD11	TD26	TL01	**TL06**	TL17	**TL09**	TL11	TR01	**TR06**	TR017	**TR09**	TR11	EU04	**EU15**	EU16	ED02	**ED14**	ED16
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7	6	3	5	5	7	7	6	1	7	7	6	7	5	7	7	6	7	5	7	7	3	7	7	2
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	6	3	5	5	7	7	6	1	7	7	6	7	5	7	7	6	7	5	7	7	7	7	7	2
3. Any other comments:			just because it's two hands											probably better to make 6 and 9 the same								beca use 1 hand				

Table 69 : Participant 10 - Abstract guided results (continued)

Abstract - guided	Extrude cut		Extrude cut shallower		Rotate clockwise				Rotate counter clockwise				Zoom in				Zoom out					Select		Deselect	
	EC12	EC13	ECS05	**ECS20**	RCW01	**RCW12**	**RCW13**	RCW19	RCCW01	**RCCW10**	**RCCW11**	RCCW16	ZI01	ZI16	ZI17	**ZI30**	ZO01	ZO16	ZO17	**ZO18**	**ZO29**	**S10**	**S11**	**D10**	**D11**
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7	7	7	7	7	7	5	7	7	7	5	7	7	7	7	7	7	7	7	7	7	7	7	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	7	7	5	7	7	7	5	7	7	7	7	7	7	7	7	7	7	7	7	7
3. Any other comments:						wouldn't differentiate between 12 nd 13	wouldn't differentiate between 12 nd 13			wouldn't differentiate between 12 nd 13	wouldn't differentiate between 12 nd 13														

Table 70 : Participant 10 - Abstract free results

Abstract - free	**Bend**	**Draw**		**Extrude cut**					**Extrude**					**Fillet**		**Join**		**Multiply/Pattern**		**Sculpt**			**Select**	**Slice**	**Undo**			**Zoom**	**Resize**	**Scale**
	Bend02	Drw19		ExtC05	**ExtC07**	ExtC08	**ExtC10**	ExtC12	Ext13	**Ext15**	Ext17	Ext20	**Ext22**	Fil05	**Fil16**	**Join01**	**Join06**	MulPat06	**MulPat07**	Scul01	**Scul02**	Scul05	Select01	Slice03	Und01	**Und02**	Und08	Zoom06	Res01	Scl01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7		7	7	7	7	7	3	7	6	5	7	7	7	7	7	7	7	7	7	2	7	7	6	6	6	2	6	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7		7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	6	7
3. Any other comments:					same as 10		same as 7			depending on if needs to be held			depending on if needs to be held			interchangeable with 6	interchangable with 1		less easy to do but more immediate and natural							probably comes from 2D				

H 2.11 Summary of all participants

Table 71 : All participants - VR results

	Translate left/right				**Translate up/down**				**Rotate CW/CCW**				**Zoom in/out**			
	TL/TR 01.2	TL/TR 01.3	TL/TR 01.1	TL/TR 03.1	TU01.6/TD01.1	TU01.1/TD01.5	TU/TD01.2	TU02.2/TD02.1	RCW/RCCW 01.1	RCW/RCCW 01.2	RCW/RCCW 01.3	RCW/RCCW 02.1	ZI/ZO 01.1	ZO05.1	ZI 02.2/ZO 04.2	Select01
1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).	6	6	6	5	6	6	6	5	6	6	4	6	5	4	4	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	6	7	5	7	7	7	5	6	5	4	6	6	7	6	7
3. Was the gesture resulted in the action you expected?	7	6	7	5	7	6	7	5	7	6	5	6	6	6	6	7
4. How difficult is it to perform the gesture (considering technology)?	6	5	7	3	6	6	7	3	7	3	2	3	5	5	3	4
5. Any other comments:	5	3	2	0	5	4	1	1	2	2	2	5	7	3	1	0

Table 72 : All participants - Abstract guided results

	Translate up						Translate down				Translate left					Translate right					Extrude up		Extrude down		
	TU01.1	TU01.2	TU02.2	TU02.3	TU02.1	TU03.1	TD01.1	TD01.2	TD02.1	TD05	TL01.1	TL01.2	TL03.1	TL01.3	TL02.1	TR01.1	TR01.2	TR03.1	TR01.3	TR02.1	EU03.1	EU02.1	ED03.1	ED01.2	ED01.1
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	4	6	5	4	4	7	5	6	2	6	6	4	5	5	6	6	5	5	5	5	5	4	6	5
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	6	6	6	6	6	7	7	6	6	7	7	6	6	7	7	7	6	6	7	7	7	7	7	6
3. Any other comments:	7	1	1	1	0	0	8	1	2	0	3	7	0	1	0	2	8	0	1	0	4	6	2	4	4

Table 73 : All participants - Abstract guided results (continued)

	Extrude cut		Extrude cut shallower		Rotate clockwise				Rotate counter clockwise				Zoom in				Zoom out					Select		Deselect	
	EC01.1	EC01.2	ECS03.1	ECS01.1	RCW02.1	RCW01.2	RCW01.3	RCW01.1	RCCW02.1	RCCW01.2	RCCW01.3	RCCW01.1	ZI01.1	ZI02.1	ZI02.2	ZI05.1	ZO01.1	ZO04.1	ZO04.2	ZO05.1	ZO07.1	S01.1	S01.2	D01.1	D01.2
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	6	5	5	6	7	5	5	4	7	5	5	4	6	4	4	4	6	4	4	4	4	6	7	6	7
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	7	7	7	6	6	5	7	6	6	6	7	7	6	7	7	7	6	7	7	7	7	7	7
3. Any other comments:	7	3	2	8	7	2	1	1	7	2	1	1	5	2	0	3	5	2	0	2	2	2	9	2	9

Table 74 : All participants - Abstract free results

	Bend	Draw	Extrude cut				Extrude					Fillet		Join		Multiply/Pattern		Sculpt			Select	Slice	Undo			Zoom	Resize
	Ben02	Drw01	ExtC02.1	ExtC05.1	ExtC06	ExtC05.2	Ext12	Ext13	Ext01.1	Ext15.1	Ext16.1	Fil04.1	Fil12	Join01	Join06	MulPat06	MulPat07	Scul01	Scul02	Scul05	Select01	Slice03	Und01	Und02	Und08	Zoom06	Res01
1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)	7	7	6	4	6	4	3	5	4	5	6	6	5	6	6	5	5	3	4	3	7	7	6	4	5	6	6
2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?	7	7	6	6	7	7	6	7	6	7	7	7	6	7	7	6	5	7	6	6	7	7	7	7	6	7	7
3. Any other comments:	0	0	4	2	2	3	0	3	0	1	7	5	5	4	6	5	4	1	4	6	0	0	4	4	2	0	0

H 3 Evaluation questionnaire

H 3.1 Part 1

Translate left/right

Translate left right version 1 (TLR1)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Translate left right version 2 (TLR2)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Translate left right version 3 (TLR3)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Translate left right version 4 (TLR4)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

When all gestures are performed:

6. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Translate up/down

Translate up/down version 1 (TUD1)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Translate up/down version 2 (TUD2)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Translate up/down version 3 (TUD3)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Translate up/down version 4 (TUD4)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy   Very easy   Easy   Neither easy nor hard   Hard   Very hard Extremely hard

5. Any other comments:
Free comment

When all gestures are performed:

6. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Rotate CW/CCW

Rotate version 1 (R1)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy   Very easy   Easy   Neither easy nor hard   Hard   Very hard Extremely hard

5. Any other comments:
Free comment

Rotate version 2 (R2)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Rotate version 3 (R3)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Rotate version 4 (R4)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

When all gestures are performed:

6. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Zoom in/out

Zoom version 1 (Z1)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Zoom version 2 (Z2)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree
4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Zoom version 3 (Z3)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Zoom version 4 (Z4)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

When all gestures are performed:

6. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Create shapes

Create a sphere (Sph)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Create a cylinder (Cyl)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Create a cube (Cub)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy Very easy Easy Neither easy nor hard Hard Very hard Extremely hard

5. Any other comments:
Free comment

Select/deselect (S/D)

1. Was the gesture you just imitated was a good match for the current command (i.e., would that gesture be a good way to execute that command).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Was the gesture resulted in the action you expected?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

4. How difficult is it to perform the gesture (considering technology)?
Extremely easy   Very easy   Easy   Neither easy nor hard   Hard   Very hard Extremely hard

5. Any other comments:
Free comment

H 3.2 Part 2 - Guided

Translate up

Translate up (TU08)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate up (TU10)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate up (TU15)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate up (TU16)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate up (TU20)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Translate up (TU24)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Translate down

Translate down (TD07)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Translate down (TD08)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate down (TD11)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate down (TD26)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Translate left

Translate left (TL01)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate left (TL06)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate left (TL17)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate left (TL09)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate left (TL11)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Translate right

Translate right (TR01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Translate right (TR06)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Translate right (TR017)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Translate right (TR09)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Translate right (TR11)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Extrude up

Extrude up (EU04)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude up (EU15)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude up (EU16)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Extrude down

Extrude down (ED02)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude down (ED14)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude down (ED16)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Extrude cut

Extrude cut (EC12)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude cut (EC13)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Extrude cut shallower

Extrude cut shallower (ECS05)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude cut shallower (ECS20)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Rotate clockwise

Rotate clockwise (RCW01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Rotate clockwise (RCW12)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Rotate clockwise (RCW13)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Rotate clockwise (RCW19)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Rotate counter clockwise

Rotate counter clockwise (RCCW01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Rotate counter clockwise (RCCW10)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Rotate counter clockwise (RCCW11)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Rotate counter clockwise (RCCW16)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Zoom in

Zoom in (ZI01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Zoom in (ZI16)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Zoom in (ZI17)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Zoom in (ZI30)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Zoom out

Zoom out (ZO01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Zoom out (ZO16)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Zoom out (ZO17)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Zoom out (ZO18)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Zoom out (ZO29)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Select

Select (S10)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Select (S11)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Deselect

Deselect (D10)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Deselect (D11)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture’s physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

H 3.3 Part 2 - Independent

Bend

Bend (Bend02)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture’s physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Draw

Draw (Drw19)

1. Was the gesture you just imitated was a good match for the current actvitiy (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture’s physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude cut

Extrude cut (ExtC01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude cut (ExtC05)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude cut (ExtC07)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude cut (ExtC10)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude cut (ExtC12)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Extrude

Extrude (Ext13)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Extrude (Ext15)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Extrude (Ext17)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude (Ext20)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Extrude (Ext22)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Fillet

Fillet (Fil05)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Fillet (Fil16)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Join

Join (Join01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Join (Join06)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Multiply/Pattern

Multiply/Pattern (MulPat06)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Multiply/Pattern (MulPat07)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want).

[They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Sculpt

Sculpt (Scul01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:

Free comment

Sculpt (Scul02)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:

Free comment

Sculpt (Scul05)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?

Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:

Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Select

Select (Select01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Slice

Slice (Slice03)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Undo

Undo (Und01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Undo (Und02)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree Disagree Mildly disagree Neither agree nor disagree Mildly agree Agree Strongly agree

3. Any other comments:
Free comment

Undo (Und08)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity).
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

When all gestures are performed:

4. In the end participant see the representations of gestures for each action and pick which one they would want to signify that command in the actual system (they can see the video of the gesture being performed if they want). [They can consider each command in isolation, i.e., they do not need to worry about whether a gesture they chose as best for one command was similar to one they already chose for another command. (This is to lessen the cognitive and memory demands on participants.)]

Gesture chosen:

Zoom

Zoom (Zoom06)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Resize

Resize (Res01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

Scale

Scale (Scl01)

1. Was the gesture you just imitated was a good match for the current activity (i.e., would that gesture be a good way to execute that activity)
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

2. Was the gesture you just tried was easy to perform (i.e., rate the difficulty of carrying out the gesture's physical action)?
Strongly disagree   Disagree   Mildly disagree   Neither agree nor disagree   Mildly agree   Agree   Strongly agree

3. Any other comments:
Free comment

H 4 Natural gestures VR/AR CAD interaction system

"Natural gestures VR/AR CAD interaction system" employs Vive headset with a LEAP sensor mounted on it, Unity, and Steam platforms and a high specification desktop computer. Detail specifications of the Vive HTC headset are given in Table 75,

Table 76, Table 77,

Table 78 and

Table 79.

Table 75 : Headset specifications

Screen:	Dual AMOLED 3.6’’ diagonal
Resolution:	1080 x 1200 pixels per eye (2160 x 1200 pixels combined)
Refresh rate:	90 Hz
Field of view:	110 degrees
Safety features:	Chaperone play area boundaries and front-facing camera
Sensors:	SteamVR Tracking, G-sensor, gyroscope, proximity
Connections:	HDMI, USB 2.0, stereo 3.5 mm headphone jack, Power, Bluetooth
Input:	Integrated microphone
Eye Relief:	Interpupillary distance and lens distance adjustment

Table 76 : Controller specifications

Sensors:	SteamVR Tracking
Input:	Multifunction trackpad, Grip buttons, dual-stage trigger, System button, Menu button
Use per charge:	Approx. 6 hours
Connections:	Micro-USB charging port

Table 77 : Tracked area requirements

Standing / seated:	No min. space requirements
Room-scale:	6’6” x 4’11” min. room size, 11’5” x 11’5” max

Table 78 : Minimum Computer Specifications

Graphics:	NVIDIA® GeForce® GTX 1060 or AMD Radeon™ RX 480, equivalent or better.
Processor:	Intel® Core™ i5-4590 or AMD FX™ 8350, equivalent or better
Memory:	4 GB RAM or more
Video out:	HDMI 1.4, DisplayPort 1.2 or newer
USB ports:	1x USB 2.0 or better port
Operating system:	Windows® 7 SP1, Windows® 8.1 or later, Windows® 10

Table 79 : Recommended GPUs for the best performance with VIVE

NVIDIA™ GeForce RTX 2080 Ti | 2080 Super | 2080 | 2070 Super | 2070 | 2060 Super | 2060	AMD Radeon™ VII
NVIDIA™ GeForce GTX 1080Ti | 1080 | 1070 | 1070Ti | 1060	AMD Radeon™ RX 5700 XT | 5700
NVIDIA™ GeForce GTX 980Ti | 980 | 970 | 780Ti	AMD Radeon™ RX Vega 64 | Vega 56
NVIDIA™ Quadro RTX 8000 | 6000 | 5000 | 4000	AMD Radeon™ RX 590 | 580 | 570 | 480
NVIDIA™ Quadro P6000 | P5000 | P4000	AMD Radeon™ R9 Fury | Fury X
NVIDIA™ Quadro M6000 | M5000	AMD Radeon™ R9 Nano
NVIDIA™ Quadro Mobile RTX 6000 | RTX 5000 | RTX 4000 | RTX 3000	AMD Radeon™ R9 390 | 390X
NVIDIA™ Quadro Mobile P5200 | P5000 | P4200 | P3200 | P3000	AMD Radeon™ R9 290 | 290X | 295X2
NVIDIA™ Quadro M5000 | M5500 | M5000 | K6000	AMD Radeon™ Pro WX 9100 | 8200 | 7100
NVIDIA™ Quadro Mobile M5500	AMD Radeon™ Vega Frontier Edition
NVIDIA™ Quadro GP100 | GV100	AMD Radeon™ Pro Duo | SSG
	AMD Radeon™ FirePro W9100

Figure 44 shows the system being used by the researcher.

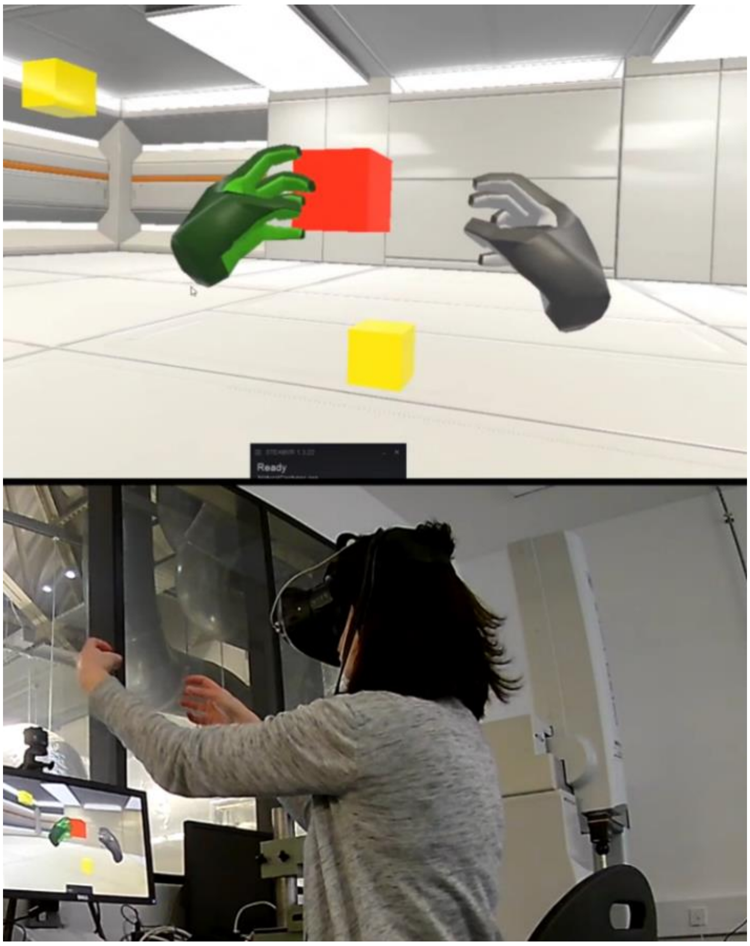


Figure 44 : Researcher interacting with a VR system used for gesture evaluation

The system supports use of 16 gestures, four for each of the activities (translate up or down, translate left or right, rotate clockwise or counter clockwise in the horizontal plane, zoom in/out):

- Four translations left and right (TLR1, where TLR stands for Translate Left Right, combining TL01.2 and TR01.2, TLR2 combining TL01.3 and TR01.3, TLR3 combining TL01.1 and TR01.1, and TLR4 combining TL03.1 and TR03.1),
- Four translations up and down (TUD1, where TUD stands for Translate Up Down, combining TU01.6 and TD01.1, TUD2 combining TU01.1 and TD01.5, TUD3 combining TU01.2 and TD01.2, TUD4 combining TU02.2 and TD02.1),

- Four rotations clockswise and counter-clockwise (R1 combining RCW01.1 and RCCW01.1, R2 combining RCW01.2 and RCCW01.2, R3 combining RCW01.3 and RCCW01.3, R4 combining RCW02.1 and RCCW02.1),
- Four zoom in and zoom out activities (Z1 combining ZO01.1 and ZI01.1, Z2 combining ZO04.1 and ZI02.1, Z3 based on ZO05.1, Z4 combining ZO04.2 and ZI02.2).

Gestures for these codes can be seen in Appendix G, Section G.5. For these sixteen activities.

The system also supports the creation of a sphere, cube, cylinder and selection and deselection of objects. However, gestures for these were not implemented based on the frequency of use of gestures derived from the gesture elicitation from the participants. They were a combination of elicited gestures and the gestures that can be easily recognised by LEAP, hence these gestures were not included in the study evaluation. They were added as an extra, to make a system more usable for demonstration purposes in possible future events.

System being used can be seen in the video provided as supplementary data.

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