

Diversity in the Mind's Eye: Defining the Mental Imagery Experience in Engineering Design

by

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A thesis submitted to the University of Strathclyde
for the degree of Doctor of Philosophy

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May 2026

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Signed: *R. Macfie*

Date: 06/05/26

For Alison, who lives on in our memories.

Previously published work

The work in this thesis partially consists of previously published work, with all outputs referenced where applicable. During the research project, the related academic outputs were one conference paper, one conference poster presentation, and one conference workshop. The published conference paper can be found in Appendix 7, the conference poster presentation in Appendix 8, the workshop proposal in Appendix 27, and the accepted abstract for the pending conference paper in Appendix 34.

Conference papers

24th International Conference on Engineering Design (2023)

“A framework for understanding mental imagery in design cognition research”

Rebecca Louise Macfie, Laura Hay, Paul Rodgers

Published within the Proceedings of the Design Society

19th International Design Conference (2026)

“Engineering Design through dialogue: A method for analysing speech-based AI conversation”

Kieran Gunn, Ross Brisco, Alexander “Freddie” Holliman, Erfu Yang, Rebecca Macfie

Accepted; pending May 2026

Design Research Society International Conference (DRS 2026)

“The Pen or the Prompt: Investigating Novice Design Students’ Use of Sketching and Generative AI for Initial Concept Visualisations”

Alexander “Freddie” Holliman, Rebecca Macfie, Kieran Gunn, Ross Brisco

Accepted; pending June 2026

28th International Conference on Engineering and Product Design Education (2026)

“Mental Imagery Vividness and its Impact on Learning Attainment in Design Education”

Rebecca Macfie, Ross Brisco

Accepted; pending September 2026

Conference poster presentation

Tenth International Conference on Design Computing and Cognition (2022)

“Understanding mental imagery in design cognition”

Rebecca Louise Macfie, Laura Hay, Paul Rodgers

Poster presented at the Tenth International Conference on Design Computing and Cognition in July 2022, Glasgow, United Kingdom

Conference workshop

27th International Conference on Engineering and Product Design Education (2025)

“Innovating Human-Centred Design Education: The Role of Mental Imagery in Inclusive learning”

Rebecca Louise Macfie, Ross Brisco, Ian Marcus Edgecomb

Workshop delivered at the 27th International Conference on Engineering and Product Design Education in September 2025, Valletta, Malta, in collaboration with the Design Education and Collaborative Design Special Interest Groups of the Design Society

28th International Conference on Engineering and Product Design Education (2026)

“Supporting Diversity of Learning in Design Education: The Sit on Your Hands Method for Concept Generation in Student Design Teams”

Rebecca Louise Macfie, Ross Brisco

Proposal under review; pending September 2026 upon acceptance

Acknowledgements

First, and foremost, thank you to Ross for his invaluable supervision during my PhD. I'm beyond grateful for all your support during a very turbulent time in my life and academic career, and for stepping in as supervisor at the halfway point in the project. Without your guidance this journey would not be ending as smoothly, or as punctually as it is. Thank you for this, and for helping me find my footing in academia.

To the staff in DMEM, and my fellow researchers in the Leonardo Suite, thank you for all the varying forms of advice, encouragement, friendship and solidarity over the years. Emma, Alan and Ian for providing advice, support or just a sympathetic ear whenever it was needed. Freddie and Rich for the support both with finding post-PhD work and by sympathising over the chaos of raising toddlers. Andrew for the much-needed guidance during my second year. Paul for his help as second supervisor on this project.

To Laura, without whom this project would not have existed: thank you for giving me the chance to take on this project and for kick-starting my passion for design research. I am so grateful to you for the opportunity to research a topic I'm constantly fascinated by.

To Ewan for making sure I remained relatively sane in this 4-and-a-half-year spell that has also seen us become parents and homeowners. Thank you for your constant encouragement, even when I'm nothing but a ball of stress. When we found out I was pregnant three years ago, you asked me to promise that I would finish my PhD... and while there have been times I've wanted to give up, and we both have much more grey hair, I did it!

To my son, Lachlan, from your appearance exactly halfway through this journey you have made everything brighter. What I've learned during my PhD is not even half of what I've learned from being your mum. I thank you for always making sure I have something to smile about, even in my most exhausted days.

To my mum, dad and Malcolm: thank you for the constant love and encouragement to always pursue my goals... and for the childcare which has been a massive help over the last 18 months. To my family and friends for all the support and understanding when I forget to reply to texts for days on end.

Finally, thank you to EPSRC for providing the funding for this project, and a huge thank you to everyone who participated in, volunteered for, or just chatted with me about this research. Without you all being so willing to share your experiences and internal thoughts, this research would not be as interesting and insightful as it is.

Abstract

The phenomenon of mental imagery is a complex experience to define, with it occurring entirely within an individual's mind, if it occurs at all. Within the field of engineering design, there is a notable absence of research and understanding on how the experience of mental imagery presents during an engineering designer's design process, with no current definition of the experience existing. The research in this thesis considers the elements of the mental imagery experience within the context of engineering design. It presents evidence of a diverse experience, a shared definition and language, and methods for implementing this knowledge into educational settings: the Experience of Visual Imagery in Design questionnaire, which proposes a new method for measuring mental imagery in engineering designers, and the Sit on Your Hands team concept generation method which encourages innovation through design by discussion alone. The research primarily considered the experiences of novice engineering designers, limiting external influences on the designers' cognition.

During the research, knowledge expansion work was undertaken to gain insight into the elements of mental imagery, and the impact in both novice and experienced designers. This was followed by the development of a framework for researching mental imagery in design cognition, categorising the elements of mental imagery into three key conceptual viewpoints: imagery modalities, dimensions of imagery ability, and imagery processes. To provide evidence for the diverse experience of mental imagery in novice engineering designers, two research studies were undertaken. Using statistical analysis, the mental imagery and design education study found and investigated a correlation between mental imagery vividness reports and engineering design module attainment, with analysis indicating that higher levels of imagery vividness equate to lower module attainment on average. The visual imagery in the design process study used protocol analysis to investigate individual novice engineering designer's mental imagery during the design process. Experience maps and Profiles of Imaging Designers were developed resulting in the documentation of a diverse mental imagery experience in engineering design, and a proposed definition.

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List of abbreviations

Abbreviation	Meaning
2D	2-dimensions
3D	3-dimensions
A-a	assumption action codes
Ap	Appearance modality
BRS	brainstorming segment
Bs	Bodily sensation modality
CA	conceptual action codes
C-a	space action codes
CBT	cognitive behavioural therapy
Da	depiction-annotations codes
D-a	depiction action codes
DEV	concept development segment
DM200	Design 2 module
DM300	Design Emotion and Experience class
DM411	Design Interaction module
DM983	Design Form and Aesthetics class
DMEM	Department of Design, Manufacturing and Engineering Management
Ds	depiction-sketching codes
Dv	dimensions of imagery ability viewpoint
DVe	emotion vividness codes
DV-imagery	vividness imagery codes
DVm	movement vividness codes
DVv	visual vividness codes
Dx	dimension codes
E&PDE	Conference on Engineering and Product Design Education
E-a	opinion or aesthetic action codes
EVA	concept evaluation segment
EVID	Experience of Visual Imagery in Design Questionnaire
FA	functional action codes

F-a	function action codes
FBS	Function-Behaviour-Structure
Fe	Feeling modality
FMIR	Framework for Understanding Mental Imagery Research
fMRI	functional Magnetic Resonance Imaging
G-a	goal action codes
GEN	concept generation segment
H-a	hand gesture action codes
I-a	issue action codes
K-a	knowledge action codes
L-a	looking action codes
Lb	looks at brief codes
Lp	looks at previous depictions codes
M-a	movement action codes
Mp	Prepares to sketch codes
MRT	mental rotation task
MSc	Masters
Mv	imagery modalities viewpoint
N-a	non-perceptual cognition action codes
NPC	non-perceptual cognition
O-a	elements action codes
P	DM300 participant
p1	participant one
P-2	Participant two
P-a	features action codes
PCC	Pearson correlation coefficients
PDE	Product Design Engineering
PDI	Product Design Innovation
PeA	perceptual action codes
PhA	physical action codes
PI	imagination imagery codes
PM	memory imagery codes
PP	intentionality imagery codes
PSIQ	Plymouth Sensory Imagery Questionnaire
PSIQ-A	PSIQ appearance

PTSD	post traumatic stress disorder
Pv	imagery processes viewpoint
Px	processing codes
Q	questions
QMI	questionnaire upon mental imagery
R	result
S-a	solution action codes
SDE	Sports Design Engineering
So	Sound modality
SOP	Style of Processing
SoYH	Sit On Your Hands design method
sQMI	Bett's questionnaire upon mental imagery
T	DM983 participant
To	Touching modality
U-a	user action codes
V-a	decision action codes
VF	form imagery codes
VG	generation imagery codes
VI	inspection imagery codes
VMIQ	Vividness Movement Imagery Questionnaire
VMIQ-2	Vividness of Movement Imagery Questionnaire 2
VP	spatial imagery codes
VR	rotation imagery codes
VS	scanning imagery codes
VT	transforming imagery codes
VVIQ	Vividness of Visual Imagery Questionnaire
VWIQ	Vividness Wine Imagery Questionnaire
VX	fixation imagery codes
Vx	visuospatial codes
W-a	working action codes
X-a	silence action codes

Chapter 1: Introduction

If asked to visualise a rose within your own mind, can you do it? If asked to imagine the smell of a rose in your own mind, can you do this? Mental imagery is a complex phenomenon to define, and researching mental imagery often feels comparable to attempting to read a person's mind. From initial research on the topic, there are many intricacies to the experience of mental imagery depending on individual cognition, warranting further exploration. The motivation for this project was to understand and define the diverse mental imagery experiences in the field of engineering design, with a focus on education and the teaching and learning of engineering design students. Having discovered that individual experiences of mental imagery differ from person to person, even amongst those working in creative fields (Gallagher 2019), the researcher was motivated to understand exactly how the experiences occur and differ within the engineering design process specifically. This chapter will introduce the key topics and phrases used within the research, alongside the overarching aim and objectives for the project, while allowing room for development as the knowledge is expanded through research activities.

Mental imagery is often described as the experience of perceiving an image within one's own mind (Pearson 2007; Nanay 2018; Maciel *et al.* 2021; Macfie, Hay and Rodgers 2023). It is similar to physical perception but with a distinct difference in the absence of any physical stimuli (Kosslyn, Behrmann and Jeannerod 1995; Maciel *et al.* 2021). It has been described as an advantageous experience, while also potentially being disruptive to design (Pearson 2019), and the cognitive abilities connected to the experience include language, memory and attentiveness (Zeman 2021). In its elementary form, mental imagery is the creation of an image in the mind that can often be manipulated and altered by the individual (Athavankar 1997).

The study of mental imagery has been compared to "mind-reading" (Zeman 2021) due to its inherently subjective nature. An individual's thoughts are fundamentally private (Pearson, Rademaker and Tong 2011), and an entirely personal experience (Athavankar 1997), making the experience of mental imagery as private and personal. It is difficult to know how well people know their own thoughts (Pearson, Rademaker and Tong 2011), making the experience entirely subjective – how can we be certain, without being able to view inside of someone's mind, that what one person is describing internally visualising is identical to

someone else's mind? This subjectivity does lead to queries such as if genuine discoveries can be made entirely within an imaged situation (Finke and Slayton 1988). Despite this, studies have shown that individuals often have a reasonable understanding of their mental imagery experience (Pearson, Rademaker and Tong 2011).

Prior to the start of the project, the researcher read an article at BBC News by Gallagher (2019), titled "Aphantasia: Ex-Pixar chief Ed Catmull says, 'my mind's eye is blind'". This article detailed how Ed Catmull, former president of Pixar and Walt Disney Animation Studios, along with Glen Keane, the creator of the Disney character The Little Mermaid, create artistically despite their experience of aphantasia – the complete lack of visual mental imagery (Zeman 2021). The discovery via this article that not every individual experiences mental imagery in the same manner was a motivation for the research project and a drive for the investigation of mental imagery in engineering design.

The field of mental imagery research is vast and ranges from psychology research and mental imagery's impact on psychological conditions, such as post-traumatic stress disorder (PTSD) (Holmes and Mathews 2010), to architecture and the interaction of mental imagery with sketching (Kavakli and Gero 2001). There are many areas of interest within mental imagery and design cognition research that could be a point of focus for the project. One of these is the implication by Gallagher (2019), that most people are incapable of drawing what they physically see, so why would there be any assumption that translating mental imagery would be the same. It was proposed by Pearson (2019), that having an individual play the video game Tetris after viewing a traumatic situation can help reduce intrusive imagery and disrupts memory experiences. Maciel *et al.* (2021), found that people without sight often experience rich mental imagery, even if it is not of the visual manner. With the vast and varied landscape of mental imagery research, it is necessary to undertake a state-of-the-art literature review (Chapter 2) to fully analyse current research, prior to defining the research focus for the project (Chapter 5).

According to Gero and Milovanovic (2020), design cognition refers to what the mind is undertaking whilst a designer is at work. Design cognition describes the cognitive processes experienced while a designer is designing (Hay *et al.* 2017), with design cognition research studying these mental processes (Hay, Cash and McKilligan 2020; Lawrie *et al.* 2024). The topic of design cognition has been researched since the 1960s (Ball and Christensen 2019; Hay, Cash and McKilligan 2020) and since then the commitment to understanding design

scientifically has continued, with focuses on elements such as design reasoning, concept generation, and decision-making (Ball and Christensen 2019). To fully understand design and design thinking, it is believed that an underlying knowledge of the cognitive processes involved is necessary (Hay, Cash and McKilligan 2020). Designers have a mental process capable of utilising and manipulating a vast array of information to generate a new solution (Kokotovich and Purcell 2000). Design cognition research pursues an understanding of the designer(s), the design process, the product (or other item being designed), and any potential user(s) (Hay, Cash and McKilligan 2020).

Much of the research on the design process and design thinking is subjective and based on the designer's own experience, and what occurs in a designer's mind is a challenging question to answer (Kokotovich and Purcell 2000). While most designers discuss having rich imagery experiences (Athavankar 1997), and it is largely considered that strong relationships exist between mental imagery and creative thinking (Rhodes 1981), the existence of designers and creatives without mental imagery (Gallagher 2019) mean that the correlation between these design elements is less than straightforward. It has been found that mental imagery supports understanding in the design process, allows better design for vulnerable users, and opens opportunities for design teams (Maciel *et al.* 2021). Despite this, education has largely neglected cognitive diversity in design, including mental imagery and visualisation considerations (Athavankar 1997), when teaching student designers.

In terms of cognitive processes, it has been discussed that mental imagery can assist the thinking process in a manner similar to sketching (Athavankar 1997). Designers often state that they consider sketching fundamental to design work, and it has been found that sketching makes less demands on the cognitive resources than mental imagery does (Athavankar 1997). With sketching being seen as an important communication and thinking aid, as well as sensitive to timing and use (Kokotovich and Purcell 2000; Heylighen and Gero 2011), it is a necessary element to consider in the conversation when discussing design cognition research and the impacts on a designer's way of working.

1.1 Aims and objectives

The drive for the research detailed in this thesis is to understand the role that the experience of mental imagery has for engineering design, and how it is defined within the field. Further, the researcher intends for the understanding of cognitive diversity in engineering designers, specifically the experience of mental imagery, to support inclusive learning in design education.

The aim of this research is to understand the experience of mental imagery, develop a common definition and language for within engineering design, and propose how to improve inclusivity in the field of engineering design and engineering design education.

Objectives are defined to achieve the research aim:

O1: Review the current state of research on mental imagery and identify a gap in the existing knowledge.

O2: Conduct interviews to establish a baseline knowledge of how designers understand their own subjective experience of mental imagery.

O3: Utilise current research to define an existing understanding of mental imagery and its role in engineering design and to develop a research focus.

O4: Develop experiments to answer research questions and bridge the identified gap in knowledge.

O5: Develop and disseminate outcomes including the development of a common language within engineering design, with a goal to improve inclusivity in the field.

The research approach and research questions are detailed in Chapter 5.

1.2 Thesis structure

While the adopted research approach and design will be detailed further in this report, the outline structure of this thesis is split into sections and chapters, starting with this introduction. The three main sections are: *knowledge expansion*, *research development* and *investigations and reflections*, before the thesis is concluded with outcomes that meet the research aim. Part A, *knowledge expansion*, consists of three chapters, the first of which

contains a state-of-the-art literature review to answer objective O1, and works to identify a knowledge gap. Chapters 3 and 4 comprise an interview study with designers across design fields to gather first-hand reports of the experience of mental imagery, and a study investigating any connections between mental imagery, emotion and design education, respectively. Part B, *research development*, finalises the research approach and design in Chapter 5 and details the development of a framework for researching mental imagery in design in Chapter 6. Part C, *investigations and reflections*, investigates the experience of mental imagery in engineering design education over two data collection and analysis studies. Chapter 7 contains the first study investigating if higher reported levels of imagery vividness will lead to higher grades in an engineering design module. The study considers student success in design classes compared with their mental imagery experience to answer whether there is a positive correlation between them. The second study explores the experience of visual mental imagery in engineering design students during their design process. Chapters 8 and 9 analyse the data collected in the study, map the experience outcomes, and develop Profiles of Imaging Designers. Finally, Chapter 10 details two key outputs for the research project: a proposed new psychometric measurement questionnaire for mental imagery in engineering design, and the verified Sit on Your Hands concept generation method for use in design teams. The thesis will be concluded in Chapter 11 with a detailed summary of the work and how the knowledge gap, research questions and project aims have been answered.

Part A: Knowledge expansion

Chapter 2: Literature review

2.1 Understanding mental imagery

2.1.1 Introduction

Despite its acknowledged importance across many scientific and creative fields (Kozhevnikov *et al.*, 2013), research on the phenomenon of mental imagery has largely centred around psychology and psychological conditions, such as obsessive-compulsive disorder (Holmes and Mathews, 2010). Within the design industry, which spans a large range of different professions and roles, the experience of mental imagery and visualisation is recognised as beneficial but is reported as being underutilised (Athavankar 1997), likely due to the questions surrounding whether or not authentic discoveries can be ‘made’ with mental imagery alone (Finke and Slayton 1998). Generally, designers are almost indifferent to mental imagery utilisation in design, due to either misunderstanding or because it is seen as a common experience, with its ease of use being almost casual for most designers (Pearson 2007; Casakin and Kreitler 2011). Despite this, evidence shows that individual experiences of mental imagery differ greatly, even amongst those working in creative fields (Gallagher 2019; Zeman 2021; Floridou, Peerdeman and Schaefer 2022).

2.1.2 Methodology

A literature review has been conducted on the current research on mental imagery in design, with the scope ranging from design to psychology, allowing an in-depth understanding of the phenomenon. While the main focus for the literature search was mental imagery in engineering design, in order to get a wide-ranging view of all related topics, the search was expanded through psychology and other design fields. A range of trusted databases and journals was used for keyword searching, primarily the University of Strathclyde Suprimo and Google Scholar databases. The keywords and phrases used were related to topics in design, through to psychology to ensure consideration of all areas of mental imagery research. Four main key phrases were searched with variations depending on the specific topic being considered: “mental imagery” (with variations including “mental imagery in engineering design”, “visual mental imagery”), “design cognition” (variations included “design cognition

research methods”), “engineering design” (variations included “engineering design education”), and “visualisation” or other terminology interpretations of the explanation of mental imagery, such as “the mind’s eye”. Following the initial search, citation searching and keyword searching of uncovered literature topics, for example the experience of synaesthesia, were utilised where necessary to further understanding. Regular searches were performed across the entire research period to ensure all current work published in journals, conferences and books was considered and the research project remained up to date.

The initial literature search between October 2021 and January 2022 returned 1,173 potentially relevant articles that was reduced to 232 during the initial review period through analysis of the abstracts, keywords, and conclusions. The initial inclusion criteria were that the paper considered mental imagery research that was undertaken in a design or creative field, expanding to architecture, for example, or that allowed for the understanding of the phenomenon itself. The included papers were further reduced to 196, with 84 included as relevant references as judged by the relevance to the research or how generalisable the literature was for within engineering design. The remainder were deemed irrelevant to the research or included in the bibliography upon reading as while they had no direct influence on the literature review, they did assist in developing an understanding of the field.

A matrix (Table 2.1) was created detailing the range of topics found in the literature, with papers grouped by common themes and topics. Topics and themes were wide-ranging across psychology and design, and included elements such as design methods, subjective responding, and design cognition. Literature was then grouped together according to similar themes of scientific understanding, imagery theme, action, and design, before the headings of “mental imagery modalities”, “mental imagery dimensions” and “mental imagery processes” were developed. Table 2.1 shows the grouping of papers included in the literature review according to their most relevant theme.

Scientific understanding	Imagery theme	Action	Design
Neurobiology	Intention	Imagery control	Design cognition
Psychology	Visual imagery	Multi-tasking	Creativity
Physical response	Auditory imagery	Cognition	Product design
Brain network	Olfactory imagery	Information processing	Engineering design
Embodied cognition	Gustatory Imagery	Dreaming	Other design
Impairment	Tractile imagery	Measures	Physical design
Mental illness	Kinaesthetic imagery	Subjectivity	Experience
Synaesthesia	Emotion	Behaviour	Teaching/training
	Spatial imagery	Perspective	Teamwork
	Object imagery		
	Visuospatial		
	Rotation imagery		
	Vividness		
	Colour		
	Style		
	Memory		
	Imagination		

Table 2.1: Subtopics gathered from literature sources

2.1.3 Overview of mental imagery as a cognitive process

Mental imagery is often described as a “perceptual experience” (Maciel *et al.* 2021) or as a “quasi-perceptual state of consciousness” (Pearson 2007) in which the mind behaves as if it is experiencing a physical sense, such as visual perception. This experience occurs entirely within one’s own mind, but it can be inspired by, and occur simultaneously to, external stimuli (Pearson 2019; Maciel *et al.* 2021), and there is little evidence to suggest that these internal mental processes are stronger or weaker than external ones (Kokotovich and Purcell 2000; Kavakli and Gero 2001). The experience of mental imagery allows individuals to access thoughts, senses and emotions entirely within their mind, and provides a strong base for creating new ideas (Palmiero *et al.* 2016).

It is explained that the function of mental imagery involves a complex brain network (Pearson 2019), of which there is evidence that the specific areas impacted are dependent on the cognitive imagery task being undertaken (Richardson 1991). If considering visual mental imagery, which is the process of visualising an image within one's mind (Zeman 2021), and physical perception, according to Dijkstra, Bosch and van Gerven (2019), imagery and perception result in similar neuroimaging responses within the brain, specifically the parietal, visual, and frontal cortex. On the other hand, during spatial mental imagery, which is the visualisation of spatial location, size and other aspects, there is evidence that the parietal cortex is active (Dijkstra, Bosch and van Gerven 2019). Additionally, there is evidence to suggest that mental imagery experiences can result in some small physical reactions within the body, such as the pupils dilating or constricting in response to imagining light or dark scenarios and objects (Laeng and Sulutredt 2014). Zeman (2021) found that during visual mental imagery, pupils can dilate in the same way as when physically perceiving a bright light. However, despite the important role of mental imagery in the lives of many people (Kozhevnikov *et al.* 2013), there is still a lack of understanding and scientific disagreement on the exact neurobiology of mental imagery, and the processes involved.

Evidence suggests high cognitive functions are needed for mental imagery processes to occur due to the complexity of the experience (Maciel *et al.* 2021). Furthermore, mental imagery can differ for many reasons, including the individual themselves, the task at hand, or any external stimuli presented (Maciel *et al.* 2021). It can include visualising parts of a project or a story then combining these within the mind, or instantaneously "seeing" the entire view in one moment (Finke and Slayton 1988), differing levels of imagery vividness (the clarity of the image) (Zeman 2021), or use of different imagery modalities from visual imagery to olfactory imagery (Maciel *et al.* 2021). The cognitive functions required can also differ slightly depending on the experience, from daydreaming to visual imagination imagery, or even dreaming (Palmiero *et al.* 2016). For example, Zeman (2021) found that an individual asked to visualise a flower would need to use cognitive functions associated with being awake and attentive, as well as language, memory, and executive function, whilst daydreaming usually does not require someone to be fully attentive. Additionally, there are many cognitive processes directly or indirectly related to imagery that both impact on it, and are impacted by it, such as eyewitness and false memory, moral decision making, reading comprehension, motor control, and sporting ability (Pearson 2019).

As internal images become more complex and more parts or features are introduced, the mental synthesis and cognitive function required will become more difficult (Kavakli and Gero 2001), but as Pearson (2007) indicated, if there was no use for mental imagery, the human mind would have no reason to spare the cognitive effort required for the experience. Over the decades, psychology and neuroscience have attempted to explain what specifically occurs during mental imagery and what can impact on it, from memory to imagination to visual stimuli (Goldschmidt 1991), but the answer is still largely unclear. Nevertheless, evidence does show that for many people, mental imagery plays an important role in their day-to-day life (Kozhevnikov *et al.* 2013).

2.2 Mental imagery in engineering design

It is believed that mental imagery occurs more instantaneously and vividly for creative individuals (Martindale 1990), that creative thought, mental imagery, and imagination are concomitant (Pearson 2007), and it is often assumed that visual mental imagery is an essential part of design cognition (Hart and Hay 2022). However, research shows that this is not necessarily the case for all designers, with reports of animation artists (Gallagher 2019) and visual designers (Zeman 2021) claiming to experience no visual imagery. Whilst it is acknowledged that engineering design is a different form of design to visual and animation art, it is possible to correlate assumptions made about creative individuals and their experiences of mental imagery (Hart and Hay 2022).

There is increasing evidence that utilising the experience of mental imagery during the design process could improve the outcomes of projects (Finke and Slayton 1988; Dahl, Chattopadhyay and Gorn 1999). Advantages of utilising the mental imagery experience in design include that it can increase synergy, require less physical ability, and allow a greater freedom of expression (Athavankar 1997; Bilda and Gero 2008). There is a simplicity that comes with designing internally (Goldschmidt 2007), partially due to the reduction in external tools needed and the ease with which new ideas can be generated. Despite evidence of the benefits of utilising mental imagery during design work, Dahl, Chattopadhyay and Gorn (1999) found that many product designers claim to not experience mental imagery at all during the design process.

There are many techniques, tools and methods that can work in conjunction with the mental imagery experience for storing, sharing, and constructing ideas and details during the design process (Goldschmidt 1994; Bilda, Gero and Purcell 2006; Goldschmidt 2007; Tedjosaputro *et al.* 2014; Tedjosaputro *et al.* 2018), such as sketching and mind mapping, but less is known about the exact experience of mental imagery within the entire design process. According to Dahl, Chattopadhyay and Gorn (1999), there is evidence to suggest that mental imagery is utilised during the development stage as this is when ideas are being generated and discussed. It has been found to be helpful during the early design stages when designers, or teams of designers, move between different details, methods, and strategies to find a solution to the problem (Tedjosaputro *et al.* 2014). Despite evidence highlighting this diverse experience, there is a significant lack of research into mental imagery in engineering design and the design process.

2.2.1 Mental imagery modalities

Visual mental imagery, often referred to as *visual thinking*, *visual perception* or *visualisation* (Goldschmidt 1994; Dahl, Chattopadhyay and Gorn 2001; Kavakli and Gero 2001; Zeman 2021) refers to the act of “seeing” within the so-called “mind’s eye”. It refers to a task that is similar to physical visual perception (Cui *et al.* 2007). Visual mental imagery is often triggered by information obtained by a stimulus other than a visual representation itself (Taruffi *et al.* 2019). In neurobiology, there is evidence to suggest that mental imagery and visual perception rely on similar neural mechanisms within the brain (Dijkstra *et al.* 2017; Dijkstra *et al.* 2019) and that impacts on visual perception can also impact on mental imagery (Pearson, Rademaker and Tong 2011). One example of this is research undertaken by Pearson, Rademaker and Tong (2011) during which individuals completed a mental imagery generation experiment in a darkened room, the results of which suggested that light can impact on the generation and storage of imagery. Commonly, visual mental imagery consists of a remembered image, either in its initial form or as a modification of remembered information (Taruffi *et al.* 2019).

The binocular rivalry paradigm is an example of imagery influencing perception, with Dijkstra *et al.*’s 2019 results showing that there appears to be a variation in the influence of imagery on conscious perception. Binocular rivalry describes the visual fight in perception of being shown two differing images at one time. Dijkstra *et al.* (2019) found that if an individual

is shown two images at one time but was asked to mentally visualise one of the images beforehand, this results in bias and the mentally visualised image is the one they will likely perceive, with this image described as having a “priming effect”. Unfortunately, the results of Dijkstra *et al.*'s (2019) study showed that the influence of imagery on perception and the relationship between this and subjective vividness ratings are too complex to draw complete conclusions, but that further work could investigate the neural links more acutely.

Mental imagery and visual perception can be considered in terms of top-down and bottom-up neural connectivity (Dijkstra *et al.* 2017; Dijkstra *et al.* 2019). Visual perception occurs from bottom-up influences throughout the visual system, starting from the retina, and whilst there is no evidence of this occurring in mental imagery, recent work shows the potential of top-down influences from the frontoparietal network to the visual areas of the brain (Dijkstra *et al.* 2017). Dijkstra *et al.*'s (2017) evidence shows an increase in bottom-up coupling between neurological brain areas during visual perception and top-down coupling during both mental imagery and visual perception, with a stronger response during mental imagery. This suggests a similarity in terms of neurological areas impacted by visual imagery and visual perception (Pearson, Rademaker and Tong 2011; Dijkstra *et al.* 2017; Dijkstra *et al.* 2019; Pearson 2019).

Visual mental imagery is recognised as a strong cognitive function within design. Often, visual mental imagery assists with the creation of a story, narrative, characters, or any other form of creative output (Taruffi *et al.* 2019). Further evidence suggests that a designer's utilisation of visual imagery during the design process can have a big impact on both the novelty and usefulness of the final design (Dahl, Chattopadhyay and Gorn 2001). The experience of mental imagery can also increase the level of empathy featured in the design process, and lead to an increased focus on the customer's perspective (Dahl, Chattopadhyay and Gorn 2001). Visual imagery encourages creative thinking and allows for easier simulation of design, making it a key tool for problem-solving (Athavankar 1997; Bilda, Gero and Purcell 2006; Bilda and Gero 2008). For designers that do experience visual mental imagery and can utilise this during design ideation, they often report this to be a starting point in the design process (Goldschmidt 2007). However, while it is often assumed that designers are inherently visual-thinking or visual-working, there is evidence of designers working in a seemingly non-visual manner (Heylighen and Gero 2011).

One way in which product designers specifically are encouraged to utilise the experience of mental imagery in design, is to visualise the end use or the customer use of a product (Herd and Mehta 2019). Evidence shows that this technique within the design process can produce a more engaging final design for the customer and can result in products that are deemed more useful (Dahl, Chattopadhyay and Gorn 1999; Herd and Mehta 2019). Further supporting this theory is Maciel *et al.*'s (2021) work showing that a designer with a disability has a higher likelihood of understanding the design requirements if they are designing for said disability.

While mental imagery is often thought to be an entirely visual experience, it is, in reality, a multisensory experience activated through the senses and can include auditory, olfactory, gustatory, tactile and motor function imagery (Goldschmidt 1994; Maciel *et al.* 2021). Whilst many people are able to experience all forms of imagery, it is not uncommon for there to be differences in the individual experience with some capable of certain modalities of imagery but not others, for example visual but not olfactory, and some experiencing different modalities at differing levels of vividness (Maciel *et al.* 2021). According to Floridou, Peerdeman and Schaefer (2021), all modalities can be associated with each other, and modality experience is based on different sensory stimuli. Research also suggests that mental imagery in one modality is often triggered by perception of a different sense, for example a specific scent triggering a visual mental image of a memory (Nanay 2018). Furthermore, the different forms of imagery can occur during, or impact the outcome of, different tasks, such as learning or problem-solving (Dahl, Chattopadhyay and Gorn 1999), and it has been suggested that intentionality of imagery, whether voluntary or involuntary, can impact the different experiences of imagery modalities (Floridou, Peerdeman and Schaefer 2021).

Research on mental imagery and its processes largely revolves around visual mental imagery, with little consideration to other modalities, particularly in design where it is often believed that visual imagery is a crucial experience (Bensafi *et al.* 2012). However, a reason for this could be a lack of understanding about what mental imagery entails and how it works. Another potential reason is that it is commonly believed, correctly or not, that visual imagery is the most dominant modality that humans experience (Bensafi *et al.* 2012). Additionally, the workings of human sensory systems differ, are flexible and tend to change or renew across lifecycles, meaning that some senses such as taste and smells can vary (Bensafi *et al.* 2012), so it is possible that imagery modality experiences fluctuate too, potentially complicating

research. While there is still limited research on the subject, it appears that imagery in design can also be multisensory, as seen in Heylighen and Gero (2011) who described the design process of an architect who lost his sight later in his career. The architect describes his design process with a great emphasis on use of touch and his memory, which produces further questions on what impact being born without sight would have on a designer's ability to design.

According to Bensafi *et al.* 2012, there is functional magnetic resonance imaging (fMRI) evidence that brain activity during olfactory imagery mimics the real-life smell sense, and that sniffing plays an important role during olfactory imagery: individuals were found to automatically sniff when asked to imagine a smell and that blocking the sniffing function impairs olfactory imagery. There is some similar fMRI evidence for the ability and physical impact of taste imagery, although this was on a far smaller scale, that found that mental imagery can have a direct impact on food cravings, with the two having a complex relationship (Bensafi *et al.* 2012).

Whilst there has been less investigation into tactile imagery, largely due to greater technical difficulties in the research and additional theoretical issues with how to measure the tactile sense, it was found to be normal for individuals to experience tactile imagery involuntarily, as with visual imagery (Gallace 2013). Furthermore, it is common for sighted individuals to resort to visual imagery whilst experiencing tactile mental imagery, referred to as "visual interference", and it is believed that vision can provoke tactile images (Gallace 2013). For the architect in Heylighen and Gero's (2011) research, touch is an important sense in his design process, as are sound and smell. Arguably most importantly for the architect's style of working is his use of gesture for communicating his ideas to others, a tool that is often seen throughout mental imagery research in design.

There is an indisputable connection between cognition and the experiences enabled by the body (Palmiero *et al.* 2009). The different mental imagery modality experiences can be utilised in psychological treatments and other real-life settings, for example, auditory imagery in cognitive behavioural therapy or taste imagery in menu creation (Nanay 2018). There is also evidence that sensory practice has immense effects on imaging ability, such as musicians outperforming non-musicians in auditory vividness questionnaires, or perfumers reporting stronger olfactory imagery than non-perfumers (Bensafi *et al.* 2012). Motor imagery, or kinaesthetic imagery, is the imaging of performing an action, or movement (Subirats *et al.*

2018). There is often confusion between the definition of visual imagery and kinaesthetic imagery, with visual being what a person sees and movement being what they feel (Roberts *et al.* 2008). The Vividness of Movement Imagery Questionnaire 2 (VMIQ-2) measures motor imagery as both an individual imaging themselves doing the movement, and visualising someone else doing it, with the two working together to determine vividness of movement imagery (Roberts *et al.* 2008). Callow and Hardy (2004) also found that kinaesthetic imagery can be used with both internal and external visual imagery, and Subirats *et al.* (2018) found that age can play a factor in kinaesthetic imagery ability, such as older subjects imaging more challenging scenarios slower than younger subjects.

An interesting discussion when considering imagery modalities is that of the connection of emotion and mental imagery. Research provides strong links between emotion and visual mental imagery, as well as indicating that trait empathy differences can be linked to higher levels of imagery (Taruffi *et al.* 2019). Mental imagery often has a greater emotional impact than verbal interpretations of potential future situations as it allows for deeper “pre-experiencing” of situations (Ji *et al.* 2022). Further evidence suggests that there is a possible emotional connection between the tendency and ability to generate mental imagery (Ji *et al.* 2022). Mental imagery plays a key role in many emotional and psychiatric disorders and treatments and there is some physical evidence that fear imaging produces a stronger response than neutral situation imaging, in that it was shown that fearful mental imagery caused an increased heart rate (Holmes and Mathews 2010). As discussed, multi-sensory mental imagery appears to mimic multi-sensory perception in those that are capable of the experience. Evidence indicates that emotional imagery works in much the same way, with an example being if an individual has a phobia of snakes, mentally visualising a snake approaching would have a similar emotional impact as physically seeing a snake (Holmes and Mathews 2010). Additionally, the nature of an image will play a role in the impact an image has, as will the emotional capabilities of the individual (D’Argembeau and van der Linder 2006; Holmes and Mathews 2010). There is evidence that the more vivid visual imagery a person experiences, the more intense and emotional any imagined future events are, and that individuals who regulate their emotions tend to have less emotional sensory experiences (D’Argembeau and van der Linder 2006; Holmes and Mathews 2010).

Perspective is an important distinction to make when discussing the impact of emotion imagery as there is evidence that field perspective versus observer perspective can change the

emotional response an image produces: if an individual visually imagines a situation happening to themselves it is likely to produce a more emotional response than if they visualise it happening to someone else (Holmes and Mathews 2010). Further, cognitive flexibility is the cognitive process of considering issues or perspectives of other people or places (Herd and Mehta 2019) or having empathy to consider other emotional states (Maciel *et al.* 2021). Finally, “reality monitoring” is the ability of an individual to distinguish between real-life and mental imagery, a process that is particularly important when accessing emotional situations in mental imagery (Holmes and Mathews 2010).

2.2.2 Mental imagery dimensions

Contrary to common belief, mental imagery is a diverse experience, with one example being that individuals can experience mental imagery at varying “strengths” (Kavakli and Gero 2001). The spectrum of mental imagery strength is often referred to as the “vividness” of mental imagery. Individuals report anywhere from a complete lack of mental imagery to extremely vivid mental imagery, and consensus leans towards vividness being a spectrum (Cui *et al.* 2007; Kozhevnikov *et al.* 2013; Pearson 2019; Bainbridge *et al.* 2021; Network 2021; Zeman 2021). Additionally, mental imagery vividness can be, and often is, modality specific (Andrade *et al.* 2014), meaning that while someone may have low vividness in one modality, they could have high vividness in another. It is believed that while imagery is a collection of abilities, vividness often reflects the various processes involved (Roberts *et al.* 2008), and evidence suggests that cultural and professional experiences have an impact on mental imagery vividness in different circumstances (Croijmans and Wang 2022). The exact neurobiology of imagery vividness is still unclear due to the subjectiveness of the experience, but it has been selectively associated with differences in top-down to early visual cortex areas of the brain (Dijkstra *et al.* 2017).

Whilst differences in imagery vividness have been discussed for decades, it was only in 2015 that the extremes of “aphantasia”, from the Greek “DeAnima”, meaning “of the soul”, and “hyperphantasia” were officially termed (Bainbridge *et al.* 2021; Network 2021). Aphantasia is the complete lack of all mental imagery (Gallagher 2019), while hyperphantasia is the opposite and describes imagery so vivid it can be characterised as feeling like a physical sensation (Bainbridge *et al.* 2021). Aphantasia is believed to affect roughly 1-3% of people, hyperphantasia around 3-7% (Zeman 2021). Milton *et al.*’s (2021) research indicates that

people with hyperphantasia perform better in memory tests than those with aphantasia, whilst people with aphantasia tend to be less extraverted and open. In design, whilst evidence shows mental imagery can improve outcomes, many designers claim to not use it, or cannot use it due to reduced vividness or aphantasia (Dahl, Chattopadhyay and Gorn 1999; 2001; Gallagher 2019). Alternative methods of designing for individuals with aphantasia include using verbal assistance to design out loud, or through the use of text to develop and communicate ideas (Bainbridge *et al* 2021).

The vividness of mental imagery can be impacted by physical or mental conditions, such as synaesthesia or brain injuries (Chun and Hupé 2016; Network 2021) and there is evidence to suggest that age can create diverse experiences (LeBoutillier and Marks 2003). Aphantasia is often congenital, although most adults knowingly living with aphantasia did not realise it existed until they were into adulthood (Rhodes 1981). However, it is also possible for aphantasia to develop as a result of a medical issue (Bainbridge *et al* 2021; Zeman 2021). One recent example is Gaber and Eltemamy (2021) who reported an individual case of acquired aphantasia following a COVID-19 infection and illness. Despite the absence of mental imagery, aphantasia does not usually have a negative impact on life experience (Bainbridge *et al.* 2021), nor does it necessarily impact on artistic or imagination abilities (Gallagher 2019; Zeman 2021). Ed Catmull, the ex-chief of Pixar, and Glen Keane, an ex-Disney illustrator, are examples of aphantasia not impacting on creative ability: both have been living with aphantasia their entire life and still find methods of creating (Gallagher 2019).

Despite investigation into aphantasia being limited, there is evidence that individuals with aphantasia tend to have more issues with “object memory” but more reliable overall memory (Bainbridge *et al.* 2021). There are also implications that vividness itself depends highly on working memory and shared knowledge (Andrade *et al.* 2014). Further evidence shows that aphantasia could be linked to issues with face recognition or autobiographical memory. On the other hand, Cui *et al.* (2007) found that highly vivid imagery can impact on autobiographical memory as the individual may be more susceptible to outside influences altering their memory. Many individuals with aphantasia still report the ability to dream as “normal”, leading psychologists to question if there is a difference between waking and dreaming imagery (Pearson 2019; Milton *et al.* 2021).

More vivid mental imagery can have a more considerable impact on physical perception (Pearson, Rademaker and Tong 2011), and highly vivid imagery can even lead to

conditions such as “Game Transfer Phenomena” where-in hallucination-like experiences occur within mental imagery following intense video game play (Floridou, Peerdeman and Schaefar 2021). Uses for extreme vividness of mental imagery include in psychiatric treatments where it has been shown that high vividness can assist in therapies such as cognitive behavioural therapy (CBT) (Pearson 2019). There have been attempts to utilise imagery in intervention therapies for psychiatric patients, such as Pearson’s (2019) study where it was highlighted how intrusive memories and thoughts following a traumatic experience can be reduced in the short term by using a distraction, such as playing the game Tetris, to move the mind away from remembered events. It has been posed that the psychological impact of highly vivid mental imagery could be multisensory, and that measuring by sense could help predict susceptibility to some psychiatric disorders (Andrade *et al.* 2014).

As well as vividness, there are other individual differences in the dimensions of imagery ability, from spatial and visuospatial, to mental rotation, to the impact of colour. This can include differences such as timing for mental rotation (Pearson, Rademaker and Tong 2011) and the speed at which individuals manipulate or process images within their mind. Evidence shows that there are large variations in mental rotation ability between individuals, and there are arguments to be made that individual variability is more significant than any found between genders (Voyer *et al.* 2020). Those with diagnosed, or self-diagnosed aphantasia consistently score as such on visual imagery vividness tests, yet often still achieve positive results on mental rotation and spatial ability tests (Keogh and Pearson 2018).

Researchers in mental rotation tend to rely heavily on theories of embodied cognition, and some suggest that this may play a role in individual differences (Voyer *et al.* 2020). Whilst standard definitions perceive cognition as a computational activity with the brain performing the operation alone, embodied cognition provides a more complex and inclusive view (Tedjosaputro and Shih 2018). It gives that cognition is more than just the ability of the brain (van der Schaaf, Bakker and ten Cate 2019), and in some respects is presented as almost the antithesis of the standard definition of cognition (Tedjosaputro and Shih 2018). Embodied cognition views thinking as an active relationship between the body, the mind, and the surrounding environment, where the body is more of a “constituent of the mind” and cognition as the body’s interaction with the world (Tedjosaputro and Shih 2018).

According to Allen (2010), the components of visuospatial imagery include mentally seeing in 2-dimensions (2D) within a 3-dimensional (3D) environment, seeing a 3D shape

from within a 2D environment, mentally rotating objects, and mentally seeing objects in scale, with evidence indicating all of these could be learned phenomena. Mental scanning is a dimensional ability which asks an individual to perceive, within visual imagery, moving from one point to another, and in tactile imagery, haptically explored maps can have a similar effect (Gallace 2013). In tactile imagery, touching establishes a relationship with an object leading to a change between a hand-centred view or an object-centred view, which could be a cause of differences in abilities (Gallace 2013). Examples of more tactile interpretations of mental imagery tasks include raised dot patterns, alphanumeric stimuli, cut-out letters, and geometric shapes (Gallace 2013). There is further evidence that higher vividness can lead to a negative impact on colour imagery and colour memory as it results in individuals being less accepting of a wider range of choice and can lead to false memories or responses (Heuer, Fischman and Reisberg 1986). When presented with images of coloured shapes or numbers and asked to visualise them in their mind later, individuals with high imagery vividness were more likely to recall the wrong colour (Heuer, Fischman and Reisberg 1986).

In relation to dimensional ability, it is noted in Pearson, Rademaker and Tong (2011) that there appears to be evidence that mental imagery can be disrupted or fail with too much focus. If an individual repeatedly attempts to manipulate or generate a visual image, there is no guarantee they will succeed each time, and could even reduce their success, for example, due to frustration or exhaustion (Pearson, Rademaker and Tong 2011). Additionally, Rademaker and Pearson (2012) showed that whilst it is likely not possible to train mental imagery ability in terms of strength or capabilities, it is possible to train understanding and recognition of mental imagery experience.

Mental imagery is a personal experience and therefore subjective (Richardson 1991), given that it occurs entirely within an individual's mind and so, the description of it relies solely on the judgement of the person (Palmiero *et al.* 2015; Milton *et al.* 2021). Unlike with physical perception, which can be compared and evaluated based on a shared external experience, mental imagery is difficult to compare and evaluate as there is no guarantee the experience is shared as described (Pearson, Rademaker and Tong 2011). As it currently stands, there is no fully accurate method of measuring mental imagery objectively, and therefore no way to know for certain what other people experience and whether their descriptions of imagery are accurate to a shared definition (Palmiero *et al.* 2015; Pearson 2019; Milton *et al.* 2021).

Psychometric questionnaires are a well-established method for measuring mental imagery vividness and experience. They attempt to quantify an inherently subjective phenomenon, and these questionnaires often take the form of “self-reporting” with scenario-style questions (Kozhevnikov *et al.* 2013). The most commonly employed of these questionnaires is the Vividness of Visual Imagery Questionnaire (VVIQ), first developed by psychologist David Marks in 1973 (Bainbridge *et al.* 2021; Network 2021). It is a written questionnaire designed to measure vividness of mental imagery through scenario-style questions (Kozhevnikov *et al.* 2013; Zeman 2021). Unfortunately, the VVIQ is not without controversy given that it does still rely entirely on subjective personal judgements of the imagery experience and only measures one modality of imagery through 16 set questions.

There have been further attempts at making the VVIQ a more wide-ranging measurement option, and new questionnaires are developed when a gap in the existing measurement systems is discovered. The solution to this can either be a new questionnaire, such as the VVIQ (Marks 1973), or an edited version of an existing questionnaire, such as the shorted form of Bett’s questionnaire upon mental imagery (sQMI), which was developed after the original questionnaire upon mental imagery (QMI) was deemed too long (Sheehan 1967). The Plymouth Sensory Imagery Questionnaire (PSIQ) is another example of a reinterpretation and was deemed an effort to fix limitations of the QMI (Andrade *et al.* 2014). Other examples include the Vividness of Movement Imagery Questionnaire 2 (VMIQ-2), which is a redesign of the Vividness of Movement Imagery Questionnaire (VMIQ, Isaac, Marks and Russell 1986) and an attempt to fix perceived confusion between the meaning of visual and kinaesthetic imagery (Roberts *et al.* 2008), and the Vividness of Wine Imagery Questionnaire (VWVQ), used to measure multisensory imagery through the imaging of an inherently multisensory task (Croijmans *et al.* 2019).

Given the subjective nature of the mental imagery experience, it has been queried whether there may be a risk that the validity of a reported experience could be disrupted by socially desirable responding (Holtrop 2021). It has been considered that social desirability scales could be used to ensure that participants are responding “truthfully”, as opposed to how they feel they are expected to respond. Social desirability scales are a psychological measure that were designed to gauge whether individuals answer self-response questionnaires or tests in “culturally sanctioned ways” but have become more commonly used to measure dishonesty or “faking” (Holtrop *et al.* 2021). The scales work by presenting the individual with questions

and scenarios which are seen to describe virtues, or negative human behaviours that most people engage in, such as lying or sharing personal information about a friend (Holtrop *et al.* 2021). It is believed that if a person responds to many of these claims in a way that depicts them as an overly virtuous person, they are more than likely lying or answering in way they deem to be socially desirable (Holtrop *et al.* 2021). As psychology research relies heavily on self-reports, social desirability scales are seen as a measure of validity for these tests, despite there being evidence that shows a positive correlation between such scores and honesty, self-control, agreeableness, conscientiousness, and humility (Holtrop *et al.* 2021). Further, social desirability scales rely solely on what the creator of the test deems to be virtuous or unvirtuous personality or behaviour traits and on subjective responses so could be flawed by the same risks. Holtrop *et al.* (2021) used think-aloud tasks undertaken by individuals in an effort to reduce subjective interpretations being invalid, with the results judged by external examiners. The examiners used set protocols to judge the participants, which led to results that indicated that social desirability scales are likely not a strong measure for dishonest responding in most circumstances, and that other methods could be sought if needed.

There are limited measurement systems available that are suitable for use in a design research setting, but protocol analysis is one suitable method that could be used to decipher mental imagery experiences in engineering design. Design is an inherently subjective and personal experience (Hay *et al.* 2017) and even the most technically skilled designers have difficulty articulating their thoughts and actions during the design process (Suwa, Purcell and Gero 1998). Protocol analysis is a design research method that uses think-aloud methods of designing (Gero and McNeill 1998; Suwa, Purcell and Gero 1998; Hay *et al.* 2017) wherein the designer is encouraged to complete a design task while discussing thoughts aloud either during the task itself or through a post-task interview. It is a method that allows researchers to view a designer's mental process whilst designing through verbalisation (Lawrie, Hay and Wodehouse 2022) and interpret their subjective reports of the designer's cognition (Hay *et al.* 2017). Despite the many benefits protocol analysis has for design research, there are some issues such as misinterpretation of a designer's description or intention of a design activity or move (Gero and McNeill 1998). Often this is circumvented through the use of two or more coders (Kavakli and Gero 2001) or the comparison of results at each stage to check for consistency and remove outliers (Gero and McNeill 1998). Protocol analysis is usually a very time-consuming method due to the high level of data gathered, but it allows detailed insights

into the internal process of a designer, making it a strong method for design cognition research (Hay *et al.* 2017).

Protocol studies are largely undertaken using video recordings of the designer during the design task to allow for collection of both verbal and visual data (Gero and McNeill 1998; Suwa, Purcell and Gero 1998; Tedjosaputro *et al.* 2018; Leblebici-Başar and Altaribba 2013; Adharamadinka and Junaidy 2022; Cindioglu, Gursel and Surer 2022). These verbal and visual recordings will then be transcribed, with notes added where necessary, and segmented into pre-determined sections (Gero and McNeill 1998; Suwa, Purcell and Gero 1998). While the method provides good insight into how a designer designs, not much is known about whether the method itself can influence a designer's process (Shealy *et al.* 2023). Shealy *et al.* (2023) found that while thinking aloud increased the number of ideas student designers generated, it reduced their design time significantly and led them to include fewer words in their sketches.

As discussed, this research results in an abundance of unstructured data and so frameworks, coding schemes and analysis methods have been developed to organise the data of these research investigations (Gero and McNeill 1998). These frameworks usually include both cognitive and exploratory design processes for designers (Hay *et al.* 2017) and consider the design process by way of the designer's place in the problem and their strategies (Gero and McNeill 1998). There are different coding schemes available for segmenting and analysing the data, and it is possible to develop a study-specific one (Tedjosaputro and Shih 2019; Cindioglu, Gursel and Surer 2022). The criteria of the scheme depends heavily on the aims and objectives of the study, and what specifically the researcher wants to answer. An example of a commonly used coding scheme is Function-Behaviour-Structure (FBS) which proposes eight fundamental processes involved in designing that allow a designer to make connections between function, behaviour, and structure in a design task (Gero and Kannengiesser 2006; Tedjosaputro *et al.* 2018). The final step of a protocol study is to analyse the coded data, and this is often undertaken through statistical or graphical analysis (Gero and McNeill 1998). Whilst protocol analysis is very resource-intensive, as the data collected is often rich but unstructured, the coding scheme and segmentation allows the researcher to organise the data in a cohesive way for analysis (Gero and McNeill 1998; Suwa, Purcell and Gero 1998; Hay *et al.* 2017).

A common method for analysing protocol data is linkography. It is a visual representation which splits the design process into "design moves" by finding connections

between the moves and constructing relationships (Kan and Gero 2008; Goldschmidt 2014; Tedjosaputro *et al.* 2018; Cindioglu, Gursel and Surer 2021). It often works in conjunction with protocol analysis, with links being created between the segmented data points and connections found between these links (Cindioglu, Gursel and Surer 2021), as well as with statistical analysis (Kan and Gero 2017). Linkography allows access to the internal thoughts of a designer at a specific time in their design process (Tedjosaputro *et al.* 2017), with benefits including that the linkographs created are scalable in 2-dimensions and flexible (Kan and Gero 2008).

There are many examples in design research of protocol analysis studies being used successfully, with most being adapted for the research in question. Some examples of different adaptations and applications of protocol analysis are as follows:

- Gero and McNeill 1998: The approach in this study uses model-based coding with codes that rely heavily on design itself. The designers were videotaped over their shoulder with speech, actions and intentions transcribed following the design task. These transcriptions were then segmented as episodes of actions and intentions, the data was coded and then categorised before analysis.
- Suwa, Purcell and Gero 1998: The actions of the participants were coded into the four cognitive levels of physical, perceptual, functional, and conceptual, with the relationships between the actions further coded. The levels were then broken down into new, continual, and revisited actions before further coding was added where necessary. This coding scheme was found to successfully consider how a designers' actions contribute to idea generation, as well as their interactions with their own sketches.
- Leblebici-Başar and Altaribba 2013: This study used the think-aloud protocols along with basic coding for visual and verbal data sets. The participants were videotaped during a design task, with the recordings then shown to the participants and their verbal reports on their thinking process during the task also recorded. Both data sets were processed and time-coded before analysis, and protocol data on both verbal recordings and sketches (visual data) was analysed.
- Cindioglu, Gursel and Surer 2022: Using a hybrid methodology of protocol analysis and linkography, two sets of protocol studies were conducted using the think-aloud

method and exit interviews. The coding scheme used in this study was productive thinking, creative thinking, idea generation, and design fixation.

- Kan and Gero 2008: By using linkography for this study, both statistical and cluster analysis was able to be undertaken on two case studies.
- Tedjosaputro and Shih 2019: The coding scheme used here consisted of cognition codes, body codes, and environment codes.
- Kavakli and Gero 2001: In order to avoid any data mistakes, the protocol data was coded by two different coders using the physical, perceptual, functional, and conceptual scheme.
- Tedjosaputro *et al.* 2018: As well as the usual video and audio recording of the think aloud method, a smart pen was also used to directly record the designers' sketches, all of which was then transcribed, segmented, coded using FBS, and analysed with linkography.

Whilst still lacking in evidence, other measures of imagery vividness have been proposed which could provide a more objective form of measurement (Bainbridge *et al.* 2021). According to Cui *et al.* (2007), it is possible that the vividness individuals experience is directly linked to the activity of their visual cortex, and it has been suggested that there could be a way to develop a method using modern technology, for example fMRI, which tracks and measures the visual cortex. While neuroimaging methods are a more complicated option due to high cost and the complexity of the equipment, it would open mental imagery research up further, for example, to the development of new communication methods (Cui *et al.* 2007). Most recently, there has been evidence found that pupil response may be an appropriate measure of aphantasia. Hawley's (2022) work has shown that when asked to mentally visualise a light versus a dark image, people living without aphantasia's pupils respond as they would to visually seeing a light versus a dark object, whereas those with aphantasia have no pupil response when given the same task. These responses were then confirmed by asking a follow-up question that involved visualising a single object versus four objects at once, finding that pupil response may provide an accurate measure of aphantasia (Hawley 2022).

2.2.3 Mental imagery processes

Mental imagery processes can take many different forms and styles, from the generation, transformation, and inspection of imagery (Rademaker and Pearson 2012) to perceptual or active imagery (Kavakli and Gero 2001), or memory or fantasy (Pearson 2007). Kosslyn, Behrmann and Jeannerod (1995) found that mental imagery involves a number of working processes that include forming, scanning, interpreting, maintaining and transforming images. The transformation from mental imagery to physical visualisation creates a form of balance between fantasy and reality that allows for more creative and novel designs (Allen 2010). Imagined objects exist within the mind and, depending on the cognitive ability of the individual, can be manipulated as real objects (Kavakli and Gero 2001). Finke and Slayton (1988) provided subjects with shapes and random parts and asked them to create images in their head leading to evidence that it is possible to make discoveries in mental imagery. The term “interactive” imagery has been used to describe the task of refining and transforming images within the mind due to the ease at which some individuals can interact with and manipulate the shapes, a process that could be of particular benefit to designers by allowing them to interact with a design in their mind (Goldschmidt 1991). According to Casakin and Kreitler (2011), designers alternate between different steps within mental imagery to navigate their way through the design process: “framing”, “making moves” and “evaluating moves”. Additionally for design, mental imagery can theoretically reduce the number of actions needed during the process (Athavankar 1997), particularly for skilled or experienced designers (Bilda and Gero 2008).

The tendency versus the ability of a designer to generate mental imagery has been queried (Ji *et al.* 2022), which could be a partial reason for the different experiences of mental imagery within design spaces. One way this can be discussed is through the intentionality of the experience of mental imagery. Mental imagery can be experienced voluntarily, through which a designer can willingly call up images within their mind, or involuntarily, for example whilst experiencing intrusive thoughts (Floridou, Peerdeman and Schaefar 2021). Goldschmidt (2007) found that experiencing mental imagery in design allows a simplicity as it can reduce the need for tools and increase idea generation with ease. Evidence also shows that a designer’s experience and intentional utilisation of visual imagery while designing can positively impact both the usefulness and novelty of the design outcome (Dahl, Chattopadhyay and Gorn 2001). Despite this, experienced designers still claim to be reluctant to use the

experience of mental imagery to assist their design process (Dahl, Chattopadhyay and Gorn 2001). It is possible that this could be explained by intentionality: if a designer assumes that their mental imagery is an involuntary or expected part of the design process, it can be theorised that they may be overlooking the potential power of voluntarily creating new ideas within their mind's eye.

One often discussed difference in form of mental imagery are the clear distinctions between mental imagery that stems from memory, and that which stems purely from imagination (Rhodes 1981; Dahl, Chattopadhyay and Gorn 1999; Dahl, Chattopadhyay and Gorn 2001; Pearson 2007; Pearson 2019). Imagination itself is defined as “the faculty of imagining; the action or process of forming such images or concepts” (Dictionary.com 2026) and whilst this can occur alongside mental imagery, images can also be as simple as remembering an image or idea that has already been defined within the memory of an individual, making the two not identical by definition (Dahl, Chattopadhyay and Gorn 1999; Dahl, Chattopadhyay and Gorn 2001; Kavakli and Gero 2001). Whilst memory mental imagery allows an individual to access the images stored in their head, imagination imagery encourages the creation of an entirely or partially new idea or thought. Imagery of all modalities is important for design, particularly visual imagery both in the form of memory visualisation and imagination visualisation (Dahl, Chattopadhyay and Gorn 1999; 2001). In design, the different imagery styles can impact on problem-solving: memory imagery allows the designer to draw from their own experiences and memory to design a product, whilst imagination imagery allows them to create entirely new ideas (Dahl, Chattopadhyay and Gorn 1999; 2001). Evidence suggests that many designers will automatically begin a design project by focusing on memory imagery before moving to imagination imagery, likely due to it being simpler to start from something they know (Dahl, Chattopadhyay and Gorn 2001). It is therefore somewhat unsurprising that Gero and Milovanovic (2020) found that designers who are experienced in their field tend to think and work faster and more intuitively than novice designers. Whilst both memory and imagination imagery are described as useful for the design process, imagination imagery has been suggested as more efficient for product ideation as it allows for a more novel product (Dahl, Chattopadhyay and Gorn 1999; Herd and Mehta 2019). On the other hand, memory images are an interesting consideration within a design team as having them available, almost like an inventory, from multiple individuals increases the number of inspiration sources, but teams may need to rely on a physical design method to communicate these images with each other (Goldschmidt 2007).

It is difficult to determine exactly what is happening within a designer's brain or mind whilst designing (Kokotovich and Purcell 2000) but there is evidence to suggest that differences occur in the cognitive actions between novice and expert designers. Image generation, for example, was found to be slower in novice designers (Kavakli and Gero 2001), whilst experienced designers were able to visualise and "think" faster (Gero and Milovanovic 2020). Kokotovich and Purcell's (2000) research highlights that design process functions and mental synthesis are likely connected to a familiarity with methods and forms within design. Further evidence indicates that interference might be an issue in mental imagery experience (Croijmans and Wang 2022), for example, eating may have an impact on gustatory or olfactory imagery or talking may impact auditory imagery.

The design thinking process is defined by Gero and Milovanovic (2020) as design cognition whilst designing. It is widely acknowledged that the initial design stages can be long-lasting and time consuming (Bilda and Gero 2008). In theory, it is possible that these stages can occur entirely within the mind through the experience of mental imagery, and that entire ideas can present themselves out with the structured segment of the process entirely (Bilda and Gero 2008). It is feasible, and not uncommon, for a designer to be working on a project then at some point later, say whilst they are having dinner or reading at night, have an idea form within their mind's eye that becomes the basis for the problem solution – this would still form part of the design thinking process and the concept generation stage, despite occurring outside of the design space (Bilda and Gero 2008). Further, there are suggestions that mental imagery could be viewed as a design tool, with researchers querying what would happen if designers had no access to sketch (Tedjosaputro *et al.* 2017) or were required to design by mental simulation alone (Christensen and Schunn 2009).

As mentioned throughout this review, the experience of mental imagery is an entirely internal process meaning that many designers often live within a catalogue of images inside their mind and design can rely on the interaction between this internal process and external processes, such as sketching and mind mapping (Athavankar 1997; Bilda and Gero 2008; Tedjosaputro *et al.* 2014). Techniques such as mind mapping encourage the designer to look for creative solutions within their own skill base and the images in their mind (Allen 2010). Most designers would argue that sketching is an essential step in the design process (Athavankar 1997; Kokotovich and Purcell 2000), with it being a simple yet reliable method of communication and reasoning within design. Sketching encourages the development of

ideas and is often seen as a crucial thinking aid (Goldschmidt 1991; Bilda and Gero 2008; Tedjosaputro *et al.* 2014). Sketching is particularly useful within design teams as it increases communication by allowing ideas and images to be shared easily (Goldschmidt 2007). Experiments have been conducted to try to explain the relationship between sketching and mental imagery over the years, but with few conclusive results. Athavankar (1997) undertook a study to investigate what would happen if a designer was unable to sketch and found that often methods such as the use of hand gestures can be used in place of sketching to encourage idea generation and communication. Similarly, Bilda and Gero (2008) found that imagery often comes before sketching, yet no further work has been undertaken to disprove that mental imagery is not experienced routinely at other points in the design process.

2.3 Discussion

Mental imagery is a phenomenon that provides access to a wealth of internal experiences within an individual's own mind (Palmiero *et al.* 2016). Following the literature review, there is an argument to be made for adapting the terminology used to discuss mental imagery. It was discovered throughout the literature review that there was no common terminology used for describing mental imagery as a phenomenon within individual cognition. It is proposed that, based on the knowledge learned throughout the literature review, the phenomenon will now be described as the *experience* of mental imagery. The review uncovered that mental imagery is experienced in very different ways from person to person, with such diversity experienced in areas from modality (Goldschmidt 1994; Maciel *et al.* 2021) to vividness (Zeman 2021) to the utilisation within design (Athavankar 1997). Describing the individual phenomenon as an experience allows for the simplification of explaining the countless ways in which the various elements of the experience interact within an individual's cognition.

A further finding of the literature review is that the investigation of mental imagery as an experience is often discussed as a singular event with little consideration of the complex elements occurring in an individual's cognition during the phenomenon. It was uncovered in the literature review that the mental imagery experience commonly consists of various elements, from memory and imagination differences (Dahl, Chattopadhyay and Gorn 1999; 2001), to rotational mental imagery ability (Allen 2010), and imagery interaction (Goldschmidt 1991). However, the researcher would argue this is often overlooked in the

literature, with the experience of mental imagery being oversimplified to a singular focus or element, such as Hart and Hay's (2022) consideration of only the impact of vividness of visual mental imagery in product design, as opposed to the various elements that may influence that vividness experience. Researchers consider mental imagery in design but without a focus on the elements involved that may impact a designer's cognitive experience (Athavankar 1997; Bilda and Gero 2008), or the interactions of sketching and mental imagery without investigating the elements involved in the generation of a mental image (Tedjosaputro *et al.* 2017). Andrade *et al.* (2014) provides a measurement of the vividness of multisensory imagery yet avoids discussion of the factors that can impact said vividness, such as if an individual can access a memory of the experience being measured, for example, the sound of a child laughing. There is an argument to be made for the necessity of a holistic approach to the investigation of mental imagery experiences, and further work in this thesis considers the various elements and viewpoints that interact within an individual's cognition, as uncovered in the literature review, in order to gain a comprehensive perspective on the experience.

One interesting understanding gained from the literature review is that mental imagery can be experienced across many sense modalities, including visual, olfactory and tactile (Goldschmidt 1994; Maciel *et al.* 2021). This multi-sensory imagery tends to mimic the real-life perception that it is correlated with, such as visual imagery mimicking real-life visual perception. The evidence found in the literature review also indicated that emotion and emotional imagery work in a similar manner, with individuals experiencing similar reactions between emotion mental imagery, and the corresponding physical emotion (Herd and Mehta 2019). This leads to the consideration of emotion as a mental imagery modality experience, with an individual's ability to image an emotion understood as a similar cognitive activity to any other mental imagery modality experienced. It would be beneficial to understand what, if any, the connections are between mental imagery and emotion with engineering design and the design process specifically, particularly within engineering design education.

Consensus amongst design cognition researchers is that the experience of mental imagery is useful but underutilised in design (Athavankar 1997), despite it being assumed to be essential in design cognition (Hart and Hay 2022). Visual imagery was found to be a strong experience in design that can assist with creative output (Taruffi *et al.* 2019) and can improve novelty and usefulness in design projects (Dahl, Chattopadhyay & Gorn 2001). Designers who reported experiencing it often report mental imagery being a starting point in their design

journey (Goldschmidt 2007). Despite this, there are many varying ways in which mental imagery is experienced in design. Designers can experience varying levels of mental imagery vividness (Kavakli and Gero 2001; Gallagher 2019; Zeman 2021), and there are many forms and styles (Kavakli and Gero 2001), such as through generation, transformation and inspection of the image (Rademaker and Pearson 2012) or rotational imagery (Allen 2010). Goldschmidt (1991) found that interactivity with mental images can be useful for designers as it can allow them to create within their mind, reducing the need for external tools. Further, intention may play an important role (Floridou, Peerdeman & Schaefer 2021; Ji *et al.* 2022), with a possible explanation for the downplaying of the experience being that if a designer's mental imagery is involuntary and occurs naturally for them, they may underestimate the potential power. Finally, there are the clear distinctions between memory and imagination imagery in design, with memory stemming from own experiences, and imagination from new ideas (Dahl, Chattopadhyay and Gorn 1999; 2001). Memory in a team setting is a particularly interesting element to consider given that it would allow for diverse inspiration sources within the design project (Goldschmidt 2007).

These experiences of mental imagery differ widely between individuals, even amongst those working in the creative fields (Gallagher 2019), and while the purpose of mental imagery could be queried, Pearson (2007) made clear that the level of cognitive effort required for the experience means that there must be a human requirement for the phenomenon. Within engineering design specifically, there is a lack of understanding about how mental imagery occurs within the design process itself, both for novice and experienced designers. While designers appear to be indifferent to the experience (Pearson 2007), could it simply be that there is a misunderstanding of the definition of mental imagery, or is the experience too casual for designers to be fully aware of it? This leads to a clear knowledge gap within the field of engineering design to understand the role of mental imagery within the design process and as part of design projects. Further, the measurement of mental imagery is thrown into focus given that there is currently no objective or subjective method for measuring mental imagery in design specifically. Protocol analysis is the most commonly used and accurate method for this through its utilisation of the think-aloud method for design (Suwa, Purcell and Gero 1998; Gero and McNeill 1998; Hay *et al.* 2017), though the exact method used would likely need to be tailored to the research. There are currently no psychometric questionnaires that measure the experience of mental imagery in design.

Finally, it is necessary to discuss the mental imagery experience in conjunction with the use of tools and methods (Goldschmidt 1994; Bilda, Gero and Purcell 2006; Goldschmidt 2007; Tedjosaputro *et al.* 2014; Tedjosaputro *et al.* 2018). There is a simplicity in the experience of mental imagery in design through its potential reduction in the need for external tools, and it could be argued to be a design tool in and of itself (Tedjosaputro *et al.* 2017). However, given the diverse experiences of mental imagery this connection is not straightforward to identify since those with no mental imagery would not have access to this internal design space. Consideration of cognitive diversity in the mental imagery experience could improve inclusivity in the field of engineering design, with it allowing for an understanding of the varying ways designers work internally. Heylighen and Gero's (2011) work with an architect who lost their sight later in life emphasises their use of memory and other senses in their design work, allowing them to continue designing despite not having the same physical access to design tools as previously. By considering the cognitive diversity that designers experience in terms of mental imagery and attempting to understand the impact on their style of working, it may be possible to develop more inclusive and useful methods and tools for engineering design and design research.

Chapter 3: Mental imagery experiences

3.1 Introduction

The literature review in Chapter 2 revealed that the phenomenon of mental imagery is not a one-size-fits-all experience, and there are intricate elements to the mental imagery experience that cannot be surmised from a review of current research alone. This is especially significant given the lack of literature relating to the experience of mental imagery in engineering design specifically. From initial discussions, it was discovered that the topic of mental imagery is a catalyst for dialogue, with individuals keen to take advantage of the opportunity to share the nuanced aspects of their mind. Unfortunately, with most discussion taking place outside of a controlled environment and in a casual setting, there is no way to validly transfer them to the research. It was therefore deemed appropriate to conduct systematic investigations by way of dialogues with design professionals in an environment where the conversations can be recorded and subsequently transcribed and analysed. Additionally, it was found during the literature review that there are a great number of different psychometric questionnaires for measuring mental imagery. It would be beneficial before going forward with the remainder of this thesis to understand how a selection of these, deemed relevant to the topic at hand, work in a real-life setting, as well as how well they work for design research. The aim of this chapter and portion of research is to understand first-hand the different experiences of mental imagery in creative professionals. The research has been developed from the gaps identified during the literature review in Chapter 2 by positioning real-life experiences alongside the literature findings, as well as being a concrete interpretation of holistic findings the researcher has uncovered through casual conversations.

3.2 Psychometric questionnaire analysis

3.2.1 Methodology

Traditionally, psychometric questionnaires measure mental imagery in a general sense, considering only, for example, visual imagery as an experience with respect to day-to-day life (Marks 1973), even if the questionnaire has been developed with a specific situation in mind (Roberts *et al.* 2008). To help develop an understanding of how mental imagery

questionnaires function in the context of engineering design and answered by a group of designers, a set of questionnaires was selected from the literature, as found in Chapter 2, and given to a group of designers from across different creative fields. The results have been analysed statistically to gain a quantitative understanding of their success when completed in a real-life setting. Additionally, participants have been qualitatively compared with interview responses of select participants to develop a deeper insight of the mental imagery experience.

The questionnaire set was presented to ten participants total, with one industry participant failing to return their set. Five of the final nine industry participants were further interviewed as detailed in Chapter 3.3. Each participant had a different design background to gain an overview of as many creative fields as possible, with the following details:

- Industry participant 1: graphic designer in private sector.
- Industry participant 2: civil engineer in refrigeration engineering.
- Industry participant 3: lecturer in design engineering.
- Industry participant 4: aerospace engineer.
- Industry participant 5: PhD researcher in engineering.
- Industry participant 6: musician.
- Industry participant 7: product developer in private sector.
- Industry participant 8: UX designer.
- Industry participant 9: researcher in engineering design.

All questionnaires were distributed as a compiled Word document with instructions, the purpose of the questionnaire, and consent confirmation. The final selection of questionnaires can be found in Appendix 1. All participants received the questionnaires in the same order and were instructed to complete them as compiled. While the order of the questionnaires was selected at random, the instructions removed any position bias variables between participants as all received the same order. Results were then catalogued in an Excel spreadsheet for ease of reading and statistical analysis. The departmental ethics committee recommended no University ethics board approval was required, and no personal information was collected and stored. All participants were asked to consent and advised of the data management procedures in place.

Questionnaires

The questionnaires were selected based due to their pervasiveness throughout the literature, with the selected questionnaires being verified for measuring mental imagery experience and regularly used in cognition studies. The questionnaires selected are:

- VVIQ (Bainbridge *et al.* 2021; Network 2021): This questionnaire measures visual imagery in different day-to-day scenarios using a measurement scale of 1-5. For the purpose of result reporting and analysis, the following scoring scale will be referred to throughout Chapter 3: 1 = aphantasia, 2 = low imagery vividness, 3 = moderate imagery vividness, 4 = high imagery vividness, 5 = hyperphantasia.
- PSIQ (Andrade *et al.* 2014): Measures imagery vividness across all modalities, including emotion, on a scale of 0-10. The following scoring scale will be used throughout analysis: 0 = possible aphantasia, 1-2 = very low imagery vividness, 3 = low imagery vividness, 4-6 = moderate imagery vividness, 7 = high imagery vividness, 8-9 = very high imagery vividness, 10 = possible hyperphantasia.
- VMIQ (Roberts *et al.* 2008): This measures the vividness of visual movement imagery, by visualising both yourself and others moving on a scale of 1-5. The following scoring scale will be used in the chapter, as per the VVIQ: 1 = aphantasia, 2 = low imagery vividness, 3 = moderate imagery vividness, 4 = high imagery vividness, 5 = hyperphantasia.
- Mental rotation task (Psytoolkit 2022): An online mental rotation task (MRT) was presented which asked participants to look at a shape then pick the correct rotated image from two possible answers provided. The results were given on speed of correct answer.
- Style of Processing (SOP) questionnaire (Childers, Houston & Heckler 1985): This questionnaire is used to determine whether an individual's processing style is visual or verbal and was deemed relevant to the study in order to find potential connections between vivid mental imagery and processing style.

Statistical analysis was undertaken on the questionnaire responses. The analysis considered mean, median, mode, standard deviation and variance calculations, as well as Pearson correlation coefficients (PCC). The individual responses to each questionnaire was

considered and comparisons made between responses by individuals, with the responses then compiled and compared between participant by questionnaire and overall findings. Finally, responses were compared to determine success of the questionnaire for the design research field and determine any correlations in responses. It should be noted that questionnaire findings are presented in order of completion by participants with variables such as questionnaire fatigue deemed inconsequential for the aim of the current investigation.

3.2.2 Results

Individual results

Industry participant one's (IP1) responses to the mental imagery questionnaires, the VVIQ, PSIQ and VMIQ, returned high overall scores, with the graphs in Figure 3.1 depicting similarly high results across the three questionnaires. The VVIQ responses returned an overall mean of 4.28 (high), with no outlier scores. The participant scored none of the questions lower than a 3.00, and scored 41% of questions a 4.00, and 44% a 5.00. The PSIQ responses returned a similarly high vividness overall mean of 7.89, with the sound modality showing the highest overall mean score at 9.00. The sound modality also featured three 10.00 scores, with the only other 10.00 score being for question four (Q4) of the appearance category. 37% of IP1's PSIQ responses were scored an 8.00, and 14% a seven, with none scored below a 5.00. The VMIQ responses had another high vividness score of 4.04, with no questions reported as less than 3.00, and 44% of questions scored a 4.00. IP1's MRT mean time was 5,857 and the overall range was 12,718. The SOP questionnaire scores were relatively even between the verbal (SW) and visual (SP) questions, with SW returning a mean of 3.00 and SP of 2.82. The most common response was 3.00 at 36% of responses for both SW and SP, and for the overall answers.

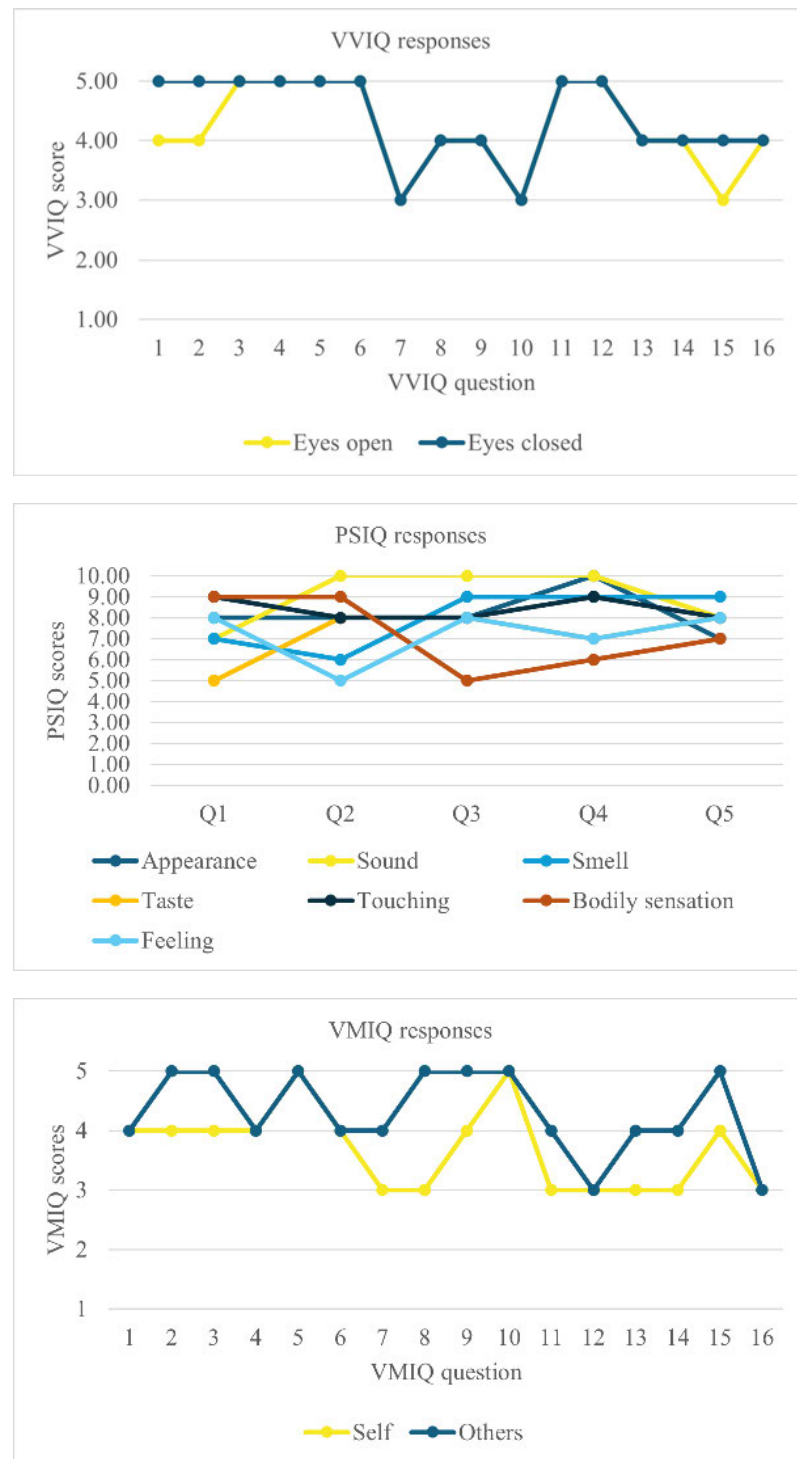


Figure 3.1: IP1 VVIQ, PSIQ and VMIQ responses

As with IP1, IP2's imagery questionnaire results were similar. Most of IP2's responses returned very high imagery scores, with some minor outliers in the VVIQ (as seen in Figure 3.2). For the VVIQ, IP2 returned a high overall mean of 4.19, with lower scores for theme one

and theme four. 44% of IP2's questions were scored at a 5.00, and none of the questions were scored at a 1.00. For the PSIQ, IP2 scored a very high vividness score of 9.11. None of their scores were less than 7.00, with 31% of scores being 9.00 and the mode score being 10.00 at 46% of total responses. All mean scores by modality are within 8.80 to 9.40, with the exception of the sound modality which returned a mean score of 9.80, as can be seen in Figure 3.2. IP2's VMIQ mean score was 4.44 which suggests high imagery vividness, although there were variations between the mean score for imaging themselves doing the task and for imaging others: they scored 4.96 for self versus 3.92 for others. 48% of IP2's VMIQ scores were 4.00, with the same percentage being 5.00, and none of the scores being less than 3.00. The mean MRT time was 1,854.40, with a range of 2,494 (695 to 3,189). Again, the SOP questionnaire responses were somewhat even between SW and SP, with SW returning a mean of 3.00 and SP of 3.45. There was more variation between answers for SW, with 36% for both 2.00 and 4.00 versus SP where 2.00 accounted for 9% of scores, and 4.00 of 55%.

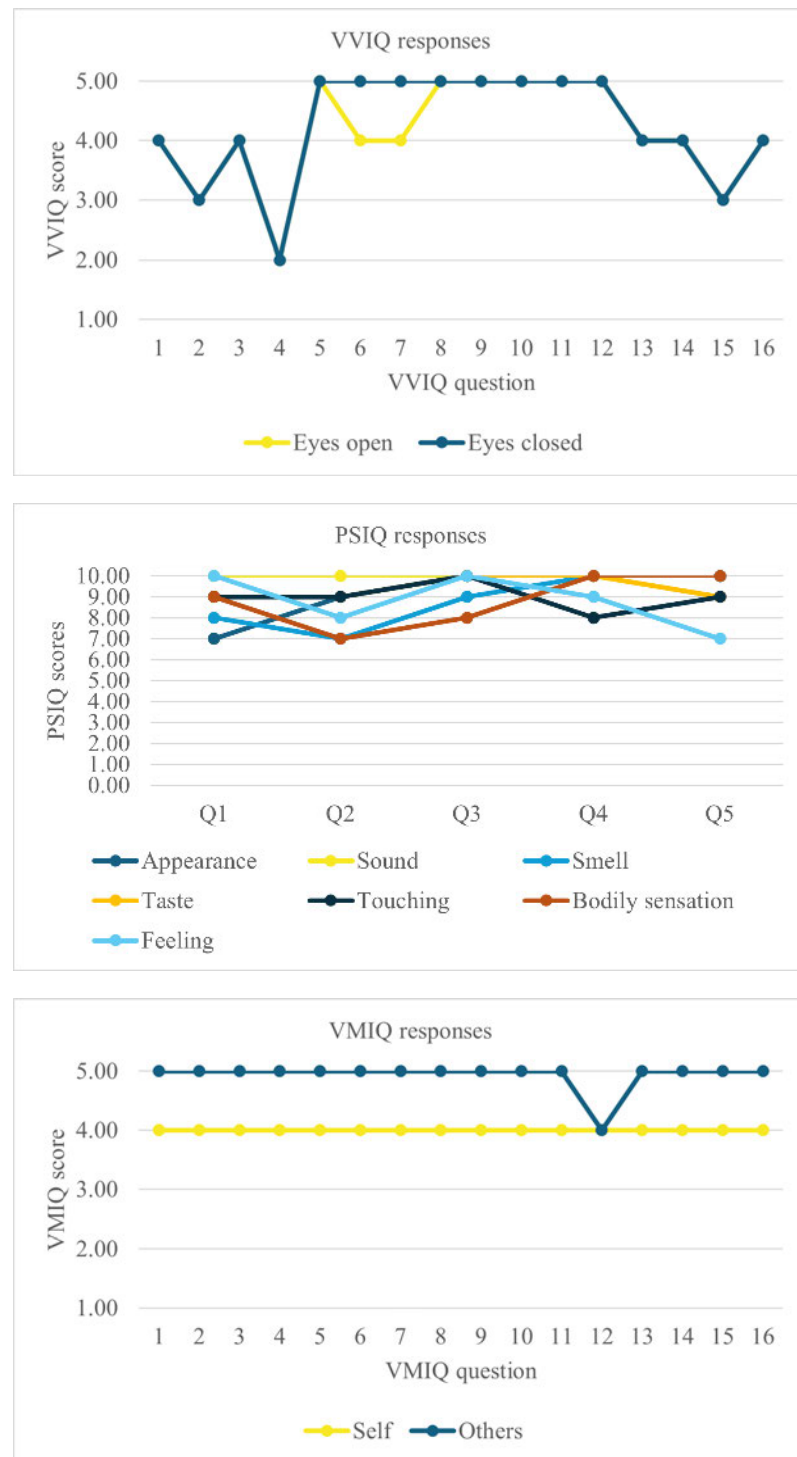


Figure 3.2: IP2 VVIQ, PSIQ and VMIQ responses

IP3's imagery questionnaires returned a reported case of visual aphantasia, with both their VVIQ and VMIQ scoring 1.00 across all questions. The PSIQ was more varied, although as per Figure 3.3, their visual imagery is reported as entirely non-existent. The PSIQ results

show all 0.00 for appearance, as with the VVIQ and VMIQ, as well as extremely low imagery vividness for both smell (0.40 mean) and taste (0.60 mean). The overall mean is 4.97, showing overall moderate level vividness when all modalities are considered, as the sound, touching, bodily sensation and feeling modalities all scored very high imagery vividness (means of 8.20 to 9.00). IP3 rated questions with a 0.00 and 9.00 (31% each), had an overall range of 10.00 and a standard deviation of 4.15. The MRT mean time was 1,803.70, with a 3,607 range, and for the SOP questionnaire, the SP score was slightly lower than SW, with SW returning a mean of 3.00 and SP of 2.00.

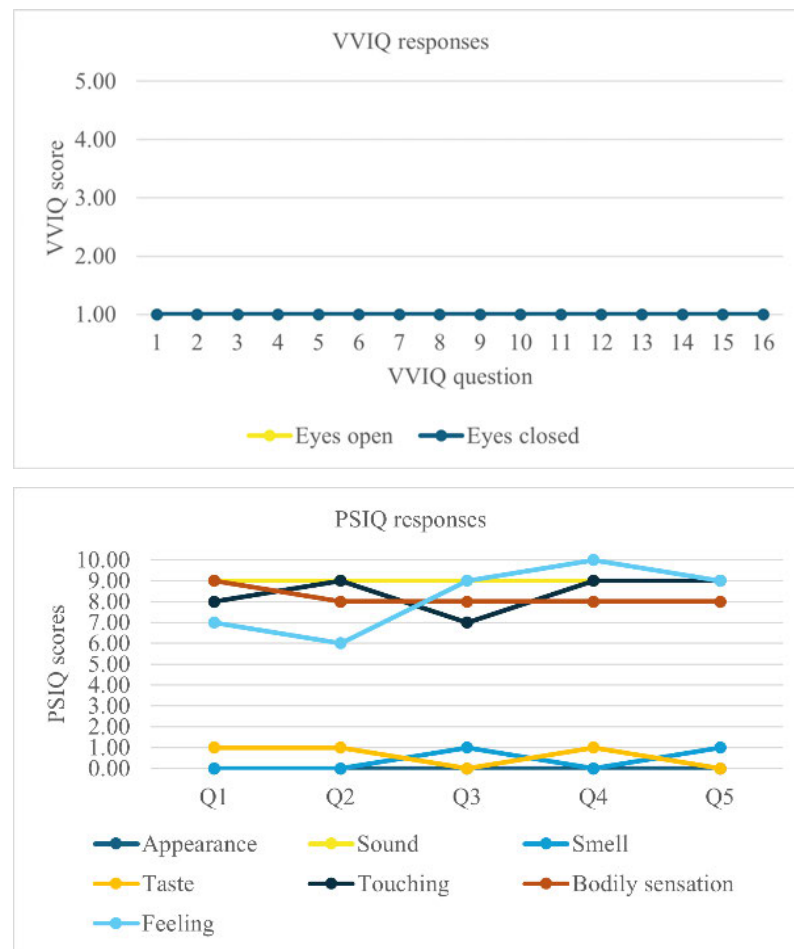


Figure 3.3: IP3 VVIQ and PSIQ responses

The imagery questionnaires for IP4 all returned low imagery vividness results, with clear aphantasia scores reported for the visual modality, and very low for all other modalities. As with IP3, the VVIQ and VMIQ were scored with all 1.00, depicting aphantasia level imagery vividness. As can be seen in Figure 3.4, the PSIQ returned very low results for all

modalities, with the overall mean 0.71 and potential multisensory aphantasia. 77% of IP4's PSIQ scores were 0.00, with no results over 4.00 and only one 4.00 score for bodily sensation, Q4. Further, IP4 only scored three questions with a 3.00, had a standard deviation of only 1.15, and a range of 4.00. For the MRT, the overall mean time was 1,776, the standard deviation 957.93, and the overall range was 2,396. Finally, for the SOP questionnaire, IP4's responses resulted in large differences between SW and SP, with SW scoring a mean of 3.00 and SP of 1.64. 46% of the SW questions were rated a 4.00, while 73% of SP questions were rated a 1.00.

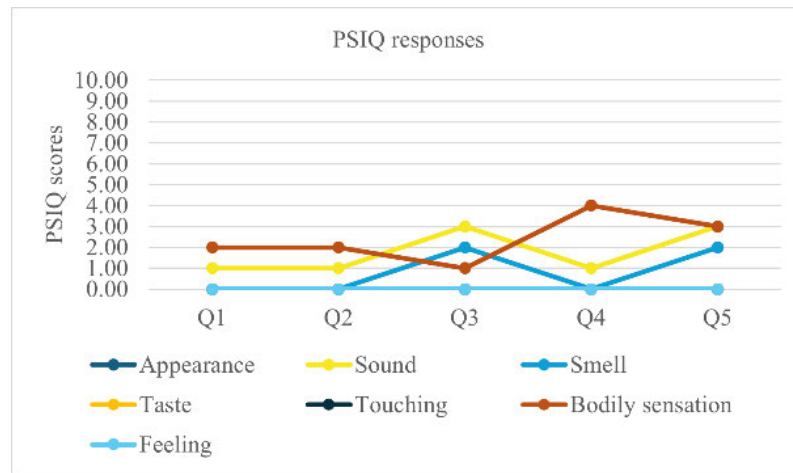


Figure 3.4: IP4 PSIQ responses

The responses to IP5's imagery questionnaires, and as can be seen in Figure 3.5, show low visual imagery vividness with some variation in other sense modalities. The VVIQ results show overall very low imagery vividness, with an overall mean of 1.66. 41% of questions were scored a 1.00, 53% a 2.00 and none of the questions were scored higher than 3.00. Q12 was the highest rated question with a score of only 3.00. The PSIQ returned an overall mean of moderate level vividness at 4.49, with scores of very low vividness for appearance and taste, versus high vividness for touching (7.40 mean). IP5 rated none of the questions at the extremes of 0.00, 9.00 and 10.00, as can be seen in Figure 3.5. Touching has the highest overall mean, and the only two 8.00 scores. IP5's VMIQ responses returned a low vividness mean score of 2.44, with 40% rated 2.00, and 52% rated 3.00. Their overall standard deviation for the VMIQ was 0.65. Their mean time for the MRT was 2,961.70, and range was 7,747. For IP5's SOP questionnaire, there was minimal variation between visual and verbal responses, and none of the questions were rated a 1.00 or 4.00. The mean scores were 3.00 for SW, and 2.45 for SP.

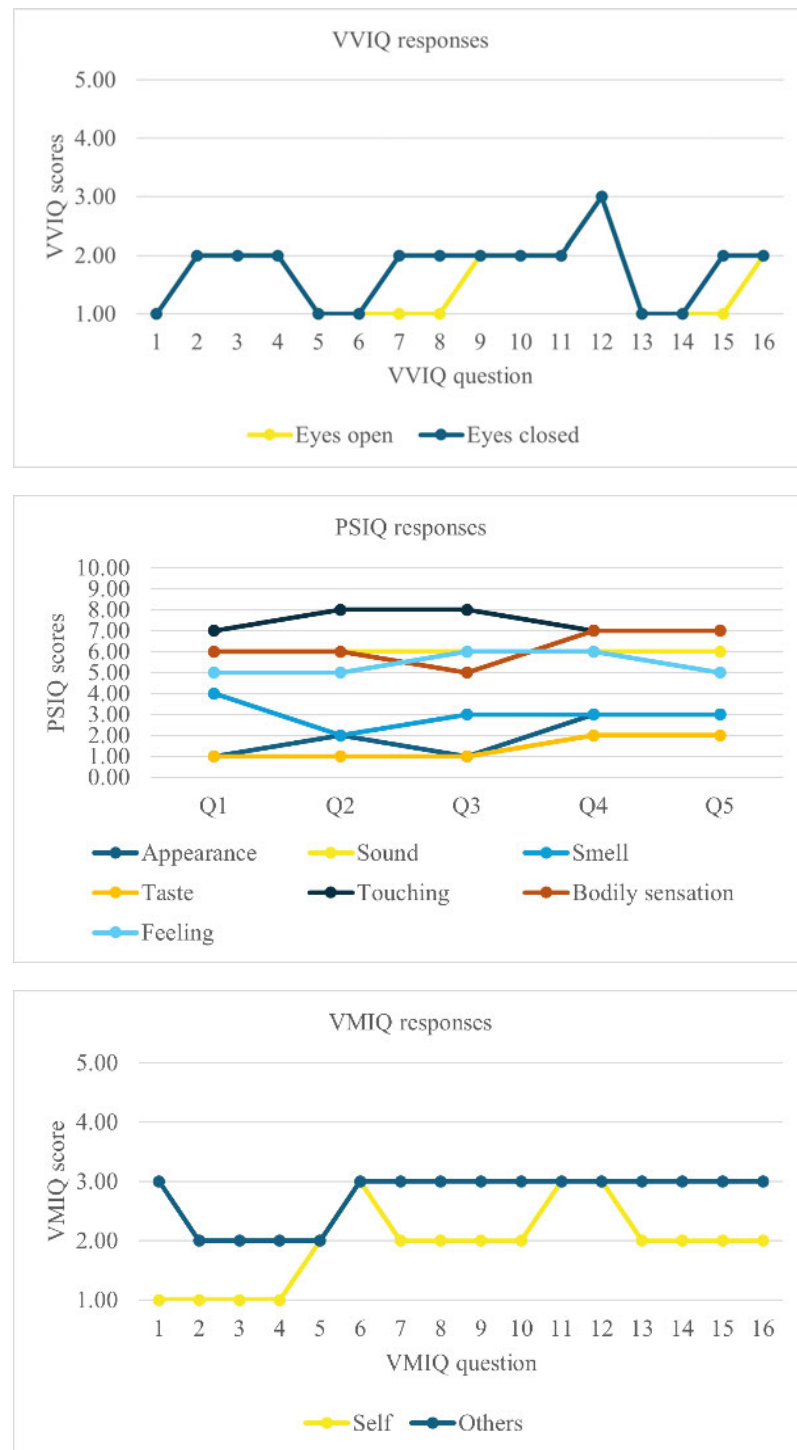


Figure 3.5: IP5 VVIQ, PSIQ and VMIQ responses

IP6 reports high mental imagery vividness across the questionnaires, as can be seen in Figure 3.6. The VVIQ mean was 4.75, suggesting hyperphantasia level imagery vividness, with 75% of the questions rated a 5.00, and a range of only 1.00. The PSIQ responses were also very high at 9.49 overall mean, and 69% of questions rated a 10.00. The standard deviation for the PSIQ was 0.89. Similarly to the VVIQ, the VMIQ returned hyperphantasia level imagery vividness with an overall mean of 4.88, 88% of ratings a 5.00 and no ratings less than 4.00. Additionally, there was no reported variation between visualising themselves doing the task or visualising someone else doing the task. The MRT mean time was 2,169.60, with a standard deviation of 1,609.29, and a range of 5,023 (from 10.00, to 5,033). IP6 scored a mean of 3.00 for both the verbal and visual questions on the SOP questionnaire.

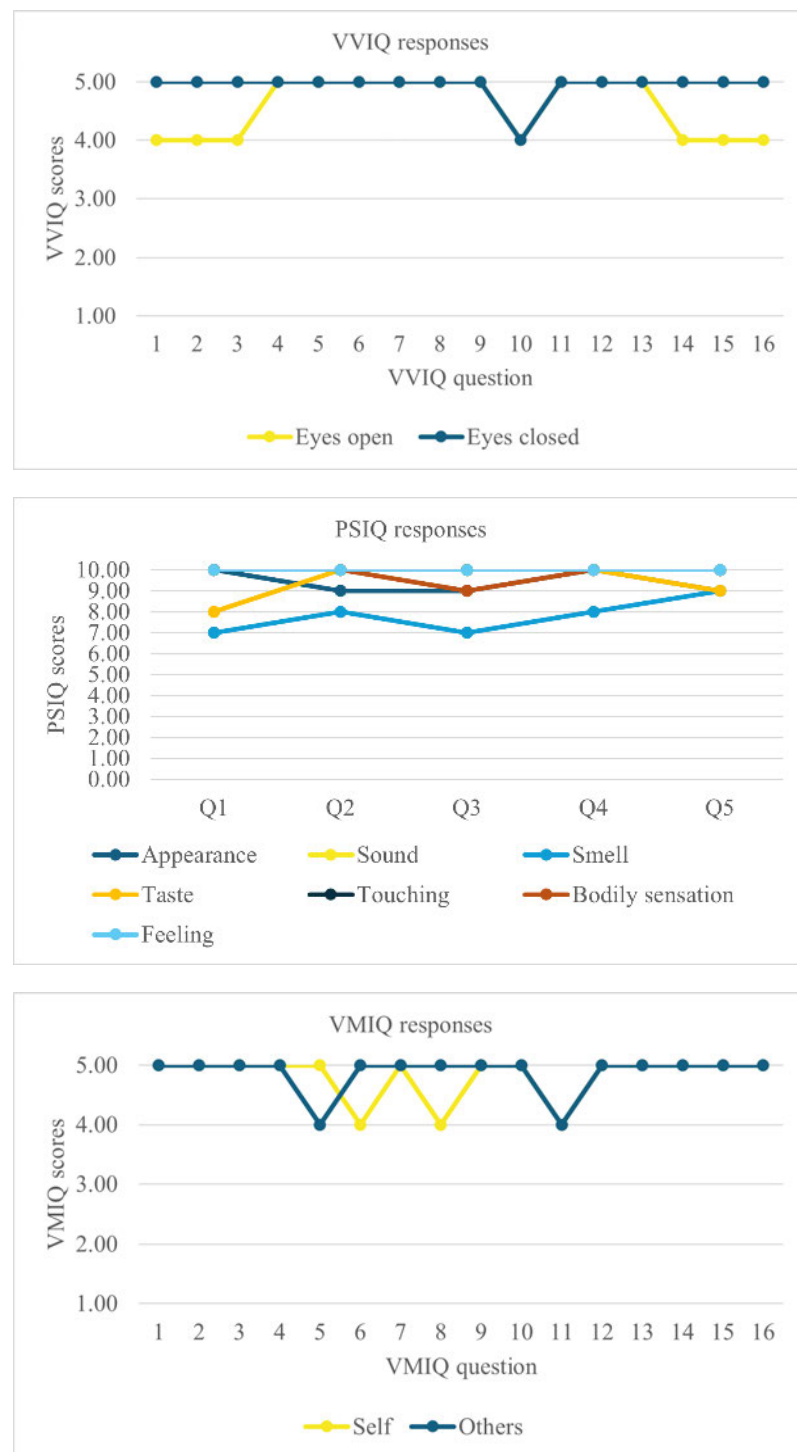


Figure 3.6: IP6 VVIQ, PSIQ and VMIQ responses

The imagery questionnaires for IP7 were, again, somewhat high across the board with a small number of outliers, as can be seen in Figure 3.7. The VVIQ responses revealed a hyperphantasia level vividness score of 4.59, and IP7 reported stronger scores for eyes closed (4.75) than for eyes open (4.44). They only rated two questions 3.00, Q1 and Q8, 66% of questions a 5.00 and none of the questions lower than 3.00. The overall range was 1.50 and standard deviation 0.49. For the PSIQ, IP7 scored an overall mean of 9.09, a very high-level vividness score. They rated 37% of questions a 9.00 and 46% a 10.00, with only one rated 6.00, and one rated 4.00, both for the taste modality (Q1 and Q5). The highest overall mean was for smell at 9.60 and the lowest was for taste at 7.60, with an overall range of 6.00 and standard deviation of 1.29, as can be seen in Figure 3.7. For the VMIQ, IP7 scored a mean of 4.10, with a big difference between their ratings for visualising doing the task themselves (4.54) and visualising someone else doing the task (3.67), evident in Figure 3.7. For visualising others doing the task IP7 rated questions with only 4.00 and 5.00, while for themselves the overall range of question scores was 4.00 and 54% of answers were a 4.00. The MRT times returned a range of 19,271, a mean of 4,352.10, and a standard deviation of 5,871.18. Lastly, IP7's SOP responses returned a mean of 3.00 for SW and 3.18 for SP, with relatively even distribution of scores between the two.

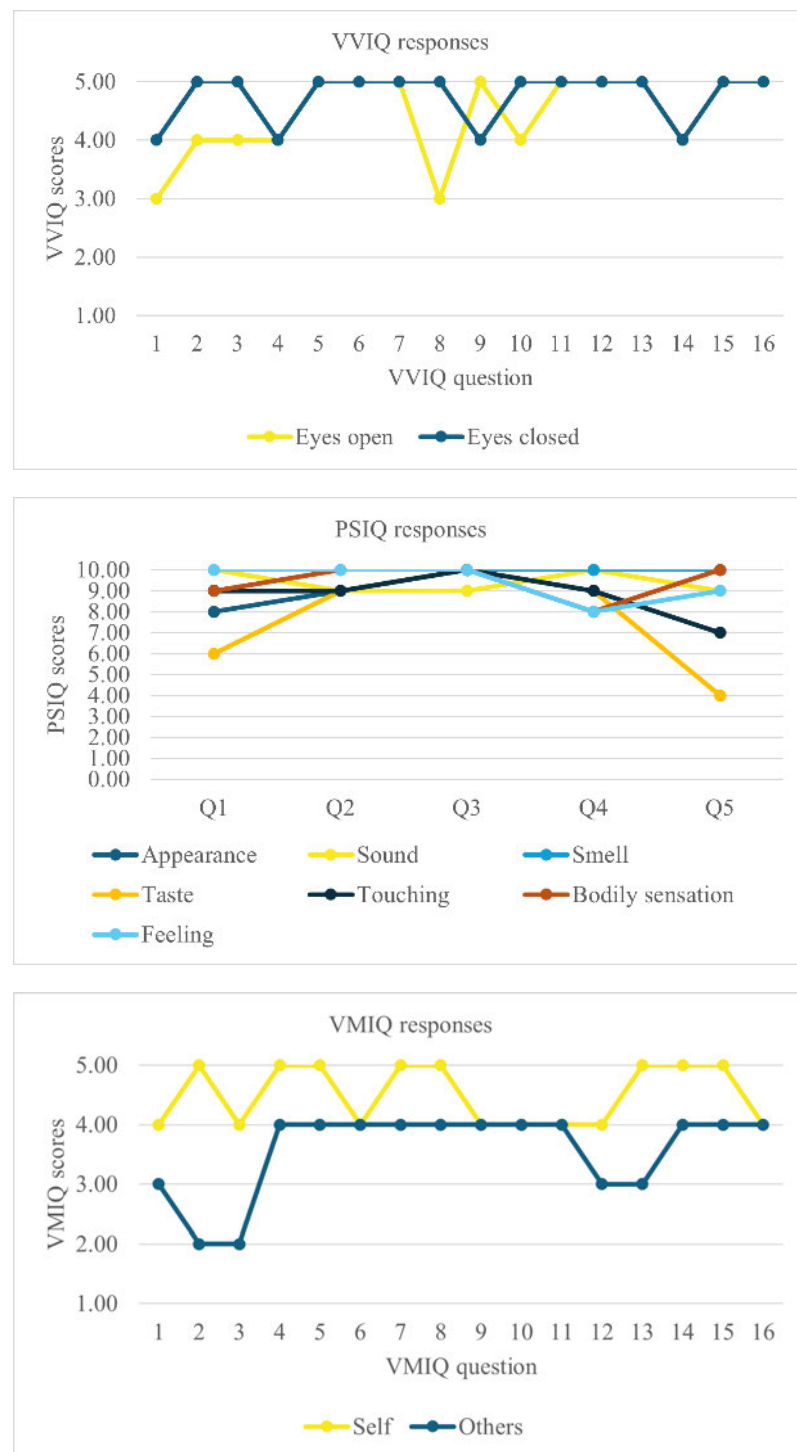


Figure 3.7: IP7 VVIQ, PSIQ and VMIQ responses

IP8 is a further participant with imagery questionnaire responses that are overall high across the board, as per the graphs in Figure 3.8. The VVIQ mean was 3.78, a high-level vividness score, with only one 5.00 for Q4, 72% of questions rated 4.00, and none under 3.00. The PSIQ responses were also high with a mean of 7.86, and only one 10.00 for appearance Q1. The taste modality was rated the highest at 9.00, and the sound the lowest at 5.60, with all sound questions rated in the moderate level vividness range. The PSIQ returned an overall range of 5.00 and a standard deviation of 1.38, with no questions rated less than 5.00 and 43% at 9.00. The VMIQ was another high-level overall mean at 4.38, with no questions rated under a 4.00, 63% rated a 4.00, and 37% a 5.00. The variance for IP8's VMIQ was 0.34. The MRT mean time was 4,076.30, with a range of 11,574 and standard deviation of 4,089.14. Finally, IP8 scored a mean of 3.00 for both verbal and visual questions in the SOP questionnaire, with scores 2.00, 3.00 and 4.00, each representing 32% of answers.

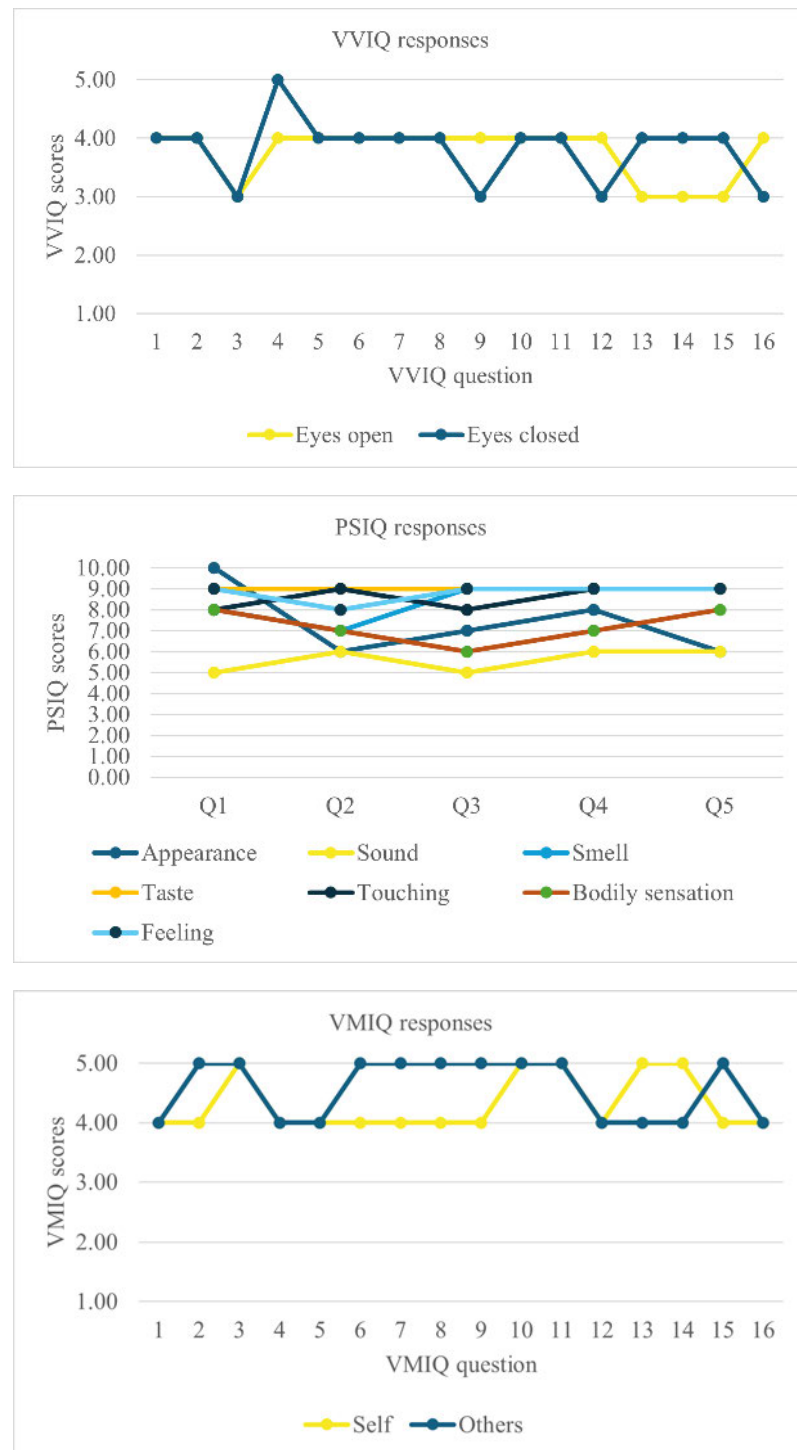


Figure 3.8: IP8 VVIQ, PSIQ and VMIQ responses

The imagery questionnaires for IP9 returned moderate imagery results for visual imagery, with the PSIQ showing higher imagery vividness across different modalities, as can be seen in Figure 3.9. IP9's VVIQ overall mean was a moderate score of 3.25, with all responses being identical between eyes open and eyes closed. The standard deviation was 0.67, 50% of scores were rated a 3.00, and none of the questions were rated at the extremes of 0.00 and 5.00. The participant scored an overall mean of 8.09 for the PSIQ which is in the very high imagery vividness range, with the results showing a range of 4.00 and standard deviation of 1.01. Only two of the questions were rated a 6.00, appearance Q5 and taste Q1. None of the questions were rated below a 6.00, while the feeling category contained the only 10.00 ratings and the only potential hyperphantasia level score of 9.60. 43% of questions were rated 8.00. The VMIQ had the same overall mean score of 3.25 as the VVIQ, with only two 2.00 ratings, 73% 3.00 ratings, and 23% 4.00 ratings. Again, there were no extremes of 0.00 or 5.00, and a standard deviation of 0.49. The MRT mean time was 4,234.40 and range was 10,014. IP9's SOP scores were similar, with SW scoring a mean of 3.00 and SP of 2.91, and no questions rated a 1.00.

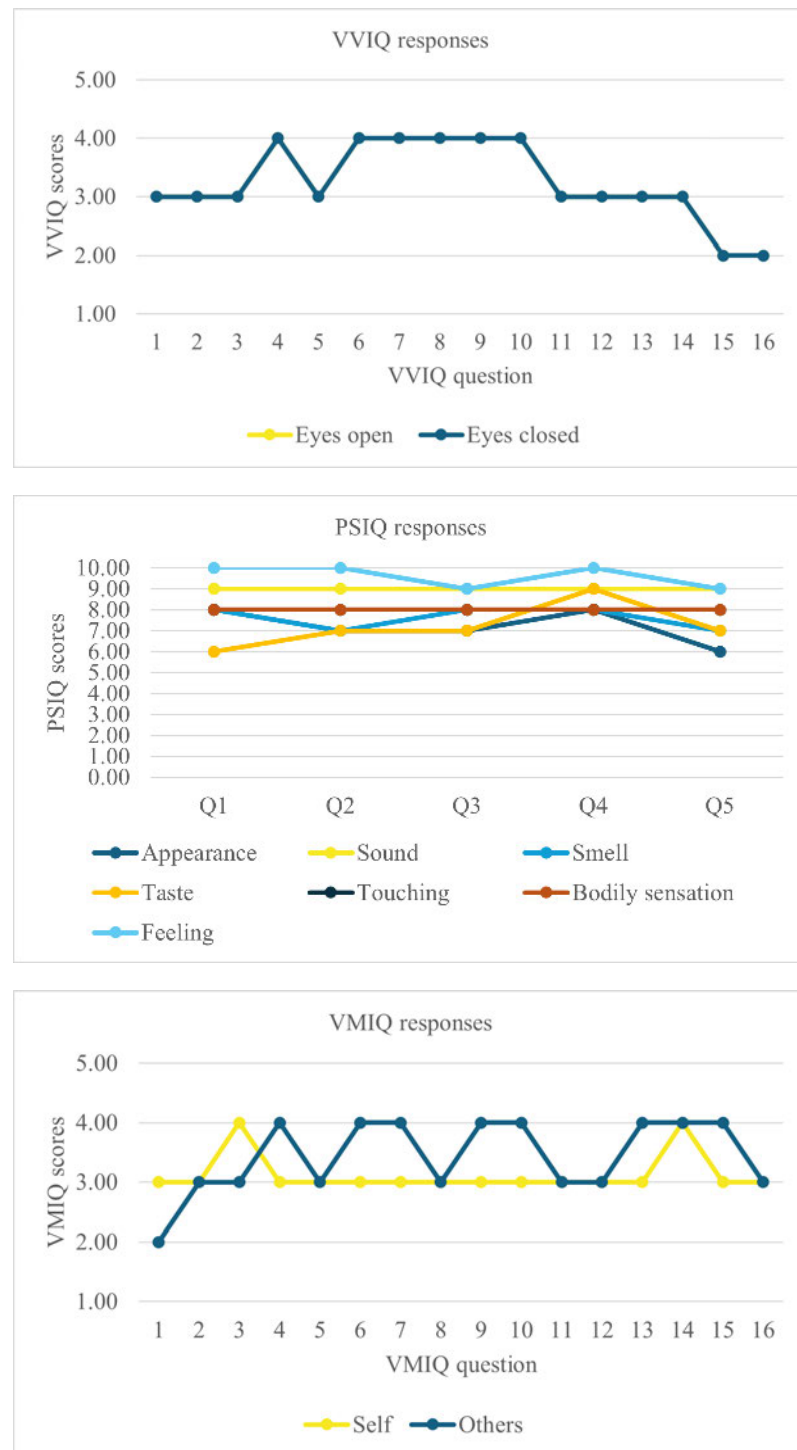


Figure 3.9: IP9 VVIQ, PSIQ and VMIQ responses

Comparisons between participants

The different questionnaires show variations between participants. The VVIQ questionnaire responses, as per Figure 3.10 returned overall mean scores ranging from 1.00 to 4.75, a standard deviation of 1.54, and an overall mean for all participants of 3.17. The greatest difference is between both IP3 and IP4 versus IP6, where IP3 and IP4 have rated all questions 1.00 while IP6's responses are all very high-level vividness scores, as seen in Figures 3.3, 3.4, 3.6 and 3.10. Similarly, the VMIQ results show variations between participants, with an overall mean of 3.28, mode of 4.50, range of 3.88 and standard deviation of 1.48. The graphs seen in Figures 3.3, 3.4, 3.6 and 3.10, again, show large variations, particularly between both IP3 and IP4 versus IP6.

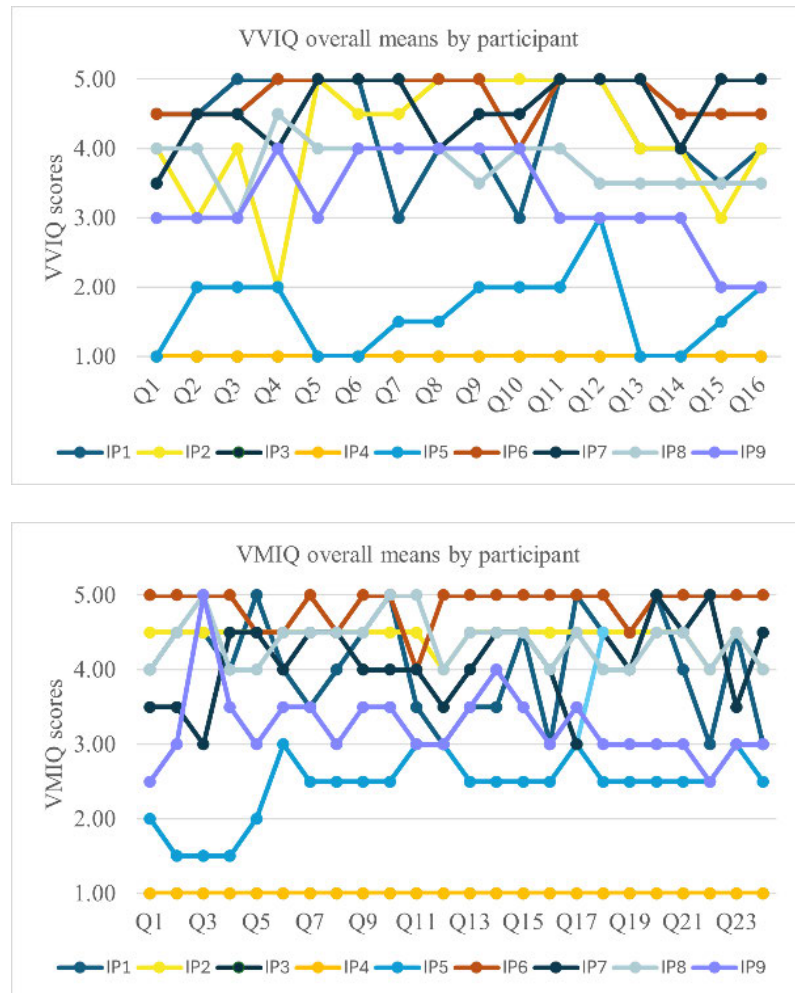


Figure 3.10: VVIQ and VMIQ overall means

Figure 3.11 highlights clear outliers in the PSIQ responses, and the results are less consistent among the responses, per participant means. The overall mode for appearance is 0.00, with overall modality means ranging from moderate to high. The overall PSIQ mean is 6.85 for all participants, and the standard deviation is 3.23. 11% of questions were rated with 0.00, 23% were rated with 9.00, and 21% with 10.00. There were more responses with extremes of 0.00 or 10.00, with ratings of 1.00 to 6.00 accounting for only 20% of total responses. As can be seen in Table 3.1 the PCCs for the PSIQ comparisons were all positive, with a large number returning strong positive correlations. The highest correlation was appearance versus smell at 0.9825 and the lowest was sound versus smell at 0.5622.

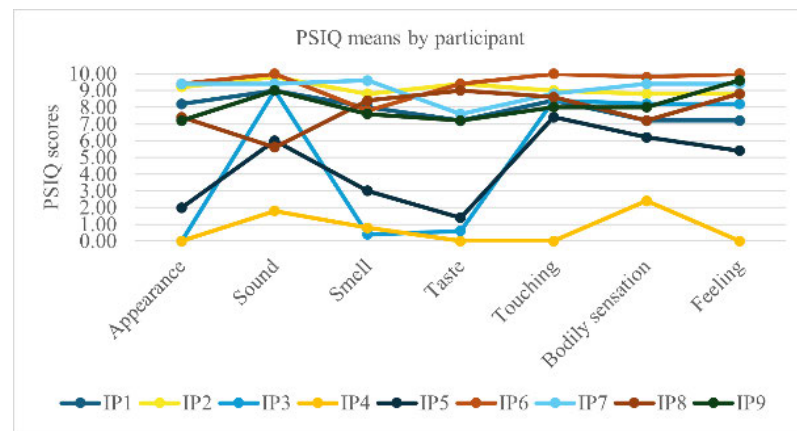


Figure 3.11: PSIQ means by modality and participant

<i>Pearson</i>	<i>Sound</i>	<i>Smell</i>	<i>Taste</i>	<i>Touch</i>	<i>Body</i>	<i>Feeling</i>
<i>Appearance</i>	0.6394	0.9825	0.9708	0.6540	0.6952	0.7124
<i>Sound</i>		0.5622	0.5914	0.8723	0.9372	0.8746
<i>Smell</i>			0.9570	0.6227	0.6369	0.6880
<i>Taste</i>				0.6651	0.6809	0.7388
<i>Touch</i>					0.9369	0.9458
<i>Body</i>						0.9579

Table 3.1: PSIQ PCCs between modalities

All participants scored below 2,500 for Q1 to Q5 on the MRT, with a large jump among all individuals after Q5. The overall mean time was 3,231.69, and range 19,990, with the biggest individual jump in Q6 from 2,290 to 20,000. A number of the participants returned similar results between the verbal and visual questions on the SOP questionnaire, with the clear exceptions being IP3, IP4, and IP5 who all scored lower on the SP questions than SW. The PCC for the SOP questionnaire results overall was 0.4103, depicting a positive correlation between the verbal and visual scores.

Comparisons between questionnaires

PCCs were calculated for various comparisons between questionnaires. The VVIQ, PSIQ, VMIQ and MRT mean results by participant were compared and PCCs calculated. As seen in Table 3.2 these returned all positive correlations. The VVIQ versus PSIQ, VVIQ versus VMIQ, and PSIQ versus VMIQ all returned positive results, with the highest being the VVIQ versus VMIQ at 0.9671. The comparisons with the MRT were lower but still positive, with the lowest being the PSIQ versus MRT results at 0.4020. PCCs were additionally calculated for the VVIQ and VMIQ versus the PSIQ appearance category only (PSIQ-A), with all positive results, Table 3.3. The VVIQ versus the PSIQ-A coefficient was 0.9902, and the PSIQ-A versus VMIQ was 0.9644. Finally, the VVIQ, PSIQ, VMIQ and MRT were compared with the SW and SP elements separately. The VVIQ, PSIQ and VMIQ versus SW all returned positive correlations, with the highest being VVIQ versus SW at 0.5871, Table 3.4. However, the MRT versus SW returned the only negative correlation at -0.1245. The VVIQ, PSIQ and VMIQ also returned strong positive correlations with SP, as seen in Table 3.4, with the highest being PSIQ versus SP.

<i>Pearson</i>	<i>PSIQ</i>	<i>VMIQ</i>	<i>MRT</i>
<i>VVIQ</i>	0.9102	0.9671	0.4836
<i>PSIQ</i>		0.8974	0.4020
<i>VMIQ</i>			0.4242

Table 3.2: PPCs between VVIQ, PSIQ, VMIQ and MRT

<i>Pearson</i>	<i>PSIQ-A</i>	<i>VMIQ</i>
<i>VVIQ</i>	0.9902	0.9671
<i>PSIQ-A</i>		0.9644

Table 3.3: PCCs between VVIQ, PSIQ-A and VMIQ

<i>Pearson</i>	<i>PSIQ</i>	<i>VMIQ</i>	<i>MRT</i>	<i>SOP-W</i>
<i>VVIQ</i>	0.9102	0.9671	0.4836	0.5871
<i>PSIQ</i>		0.8974	0.4020	0.2976
<i>VMIQ</i>			0.4242	0.5703
<i>MRT</i>				-0.1245

<i>Pearson</i>	<i>PSIQ</i>	<i>VMIQ</i>	<i>MRT</i>	<i>SOP-P</i>
<i>VVIQ</i>	0.9102	0.9671	0.4836	0.9015
<i>PSIQ</i>		0.8974	0.4020	0.9364
<i>VMIQ</i>			0.4242	0.9277
<i>MRT</i>				0.3766

Table 3.4: PCCs between VVIQ, PSIQ, VMIQ, SOP-W and SOP-P

3.2.3 Analysis

The imagery questionnaire results for IP1 were consistent across all three questionnaires: VVIQ, PSIQ and VMIQ. This is evident in the graphs in Figure 3.1 which clearly show high overall scores and ratings above moderate level imagery vividness. The VVIQ, VMIQ and PSIQ-A all have similarly high-level imagery vividness results which shows a clear representation of high imagery vividness in the visual modality. Further, the overall mean for the VVIQ is 4.28 and VMIQ is 4.04 showing definitive similarities between IP1's visual and visual movement imagery experiences. To compound IP1's high level vividness scores, neither the VVIQ or VMIQ had any scores below 3.00 (moderate level vividness) and the PSIQ had none below 7.00 (high level vividness). The results alongside IP1's work as a graphic designer in the private sector support the suggestion that creative individuals often experience strong visual mental imagery (Martindale 1990; Pearson 2007). An interesting point to note with IP1's results is that their PSIQ sound results were notably high, with multiple 10.00 ratings. The participant attends private singing classes in their spare time and is a member of a local choir. As is shown in Bensafi *et al.* 2012, musicians often perform better in auditory imagery tests than non-musicians, which could explain this particularly high result.

IP2 trained as a civil engineer but is working in refrigeration engineering as a member of a design team. IP2's VVIQ, PSIQ and VMIQ also show consistent results and high averages across the three questionnaires, as is evident in the graphs in Figure 3.2. While the VVIQ and VMIQ have similar overall mean scores (4.19 and 4.44 respectively), there are some notable differences in the VMIQ between the ratings for imaging someone else completing the task

and imaging the self, suggesting IP2 finds it slightly more difficult when asked to experience visual movement imagery in first person. Further, the VVIQ had some outliers in theme one (a relative or friend) and theme four (natural scene: lake). As will be discussed further in Chapter 3 during the interview study, IP2 noted during the interview that they struggle with visualising and remembering faces, which could have contributed to the lower scores on theme one. To further confirm the high average results, no ratings for the PSIQ were below 7.00 (high), and none of the VMIQ were below 3.00 (moderate), while almost half the VVIQ and VMIQ scores were a 5.00, and almost half the PSIQ scores a 10.00, all of which are the highest possible ratings. These consistently high ratings indicate that IP2's mental imagery experience is reliably reported within the modality that is being experienced.

IP3 is a lecturer in design engineering and was interviewed for the study after contacting the research supervisor to report their experience with aphantasia. The aphantasia report is clear within the VVIQ, PSIQ-A and VMIQ responses, with the participant ranking all 0.00 or 1.00, dependent on the measurement system in question, and can be seen clearly in the graphs in Figure 3.3. IP3 is an example of a creative professional whose experience in mental imagery is unexpected, with them having a successful design career despite reporting no visual mental imagery. Of interest is that IP3's PSIQ results are varied, with extremely low results for smell and taste, but very high mental imagery vividness reported for sound, touching, bodily sensation and feeling. This is clear in the graphs in Figure 3.3, where a large gap can be seen between the lowest ratings and highest ratings and leading to the overall mean of 4.97 (moderate level imagery vividness). Despite these differences between modalities, IP3 is another participant with consistent imagery vividness within the modality itself, showing that their mental imagery experience appears less impacted by the specific question being asked.

IP4, an aerospace engineer in the academic sector who also got in touch with the research supervisor to report aphantasia, reported the same results in the VVIQ, PSIQ-A and VMIQ as IP3, with 0.00 and 1.00 scores across the questions depending on the measurement system. The graphs in Figure 3.4 clearly demonstrate these results. While IP4's visual imagery results show clear visual aphantasia, in contrast to IP3's PSIQ results, IP4's overall mean is only 0.71 and their mental imagery across all modalities is extremely low. Over 75% of the PSIQ ratings were 0.00, with no ratings over 3.00, the exception being for bodily sensation Q4, jumping in the pool, which was rated at a 4.00. The PSIQ range was 4.00, which is remarkably low compared with IP3's PSIQ range of 10.00. Not only does this show clear

distinctions in the mental imagery experience between IP3 and IP4, where IP3 has varied experiences across modalities while IP4 has consistently low mental imagery vividness, but it also suggests potential multisensory aphantasia in IP4. While currently the definition for aphantasia refers to visual mental imagery (Zeman 2021), it would be interesting to understand if this can be expanded across other modalities.

IP5 is the final participant who contacted the research supervisor reporting aphantasia and is a researcher in engineering. Despite their verbal report of aphantasia, their imagery vividness questionnaires show consistently very low imagery vividness but no complete aphantasia, particularly when comparing the graphs in Figure 3.5 to IP3 or IP4's graphs in Figures 3.3 and 3.4. There were clear distinctions between the participant's VVIQ and VMIQ results which is a change from the previous four participants. The VVIQ overall mean is 1.66, while the VMIQ is 2.44. Further, over 90% of the VVIQ answers were 1.00 or 2.00, while over 50% of the VMIQ answers were 3.00. These differences between the two questionnaires are interesting when considering IP1 to IP4's VVIQ and VMIQ questionnaires results were all similar respectively. IP5's PSIQ results revealed moderate mental imagery vividness overall, with high imagery vividness as an outlier in the touching modality. None of IP5's PSIQ scores were of the extremes of 0.00 or 10.00, which is clear from the graph in Figure 3.5. IP5's interview responses will be discussed further in Chapter 3 and analysed alongside the results found in the questionnaires for more understanding of the aphantasia report.

The mental imagery questionnaire results for IP6 revealed consistently high mental imagery vividness across modalities, despite IP6 having no design background and not working in a creative field. The graphs in Figure 3.6 clearly depict these high vividness results. Again, IP6's VVIQ and VMIQ overall mean scores were similar: 4.75 and 4.88 respectively. Furthermore, 75% of the VVIQ questions were scored a 5.00, almost 70% of the PSIQ questions were scored a 10.00, and over 87% of the VMIQ questions were scored a 5.00, the highest possible ratings for each questionnaire. IP6 is a part-time musician currently working in a public sector role, so it is interesting that they returned the highest overall results of the nine participants.

The most notable difference in IP7's imagery questionnaire responses, as is clear through the variation seen in the graphs in Figure 3.7, is the lower level of consistency in the responses per questionnaire. While IP1 to IP6 revealed consistency in their answers within each questionnaire and modality, IP7's responses were slightly more varied and unpredictable.

Despite this, their VVIQ and VMIQ overall mean responses were expectedly similar at 4.59 and 4.10 respectively. The VMIQ revealed a greater difference between the two categories with visualising themselves doing the task scoring a mean of 4.54 and visualising others of 3.67. The lack of consistency suggests differences in the ways in which they experience visual mental imagery and is interesting to compare to IP2 who's experience seemed the opposite, with IP2 scoring higher when visualising others doing the task. While IP7 did respond with some outliers, the VVIQ still had over 65% of responses at a 5.00, and the PSIQ with over 80% at a 9.00 or 10.00, resulting in a high overall mental imagery vividness score.

IP8 is a UX designer in the private sector and, as is clear from the graphs in Figure 3.8, returned all high mental imagery vividness results across the three questionnaires. The VVIQ overall mean was 3.78, high-moderate level vividness, which is lower than the other designers without aphantasia, and only one question was rated 5.00 (Q4: clothing of a friend or relative). The VMIQ, however, scored a higher overall mean of 4.38, with no questions rated below a 4.00 and a variance of only 0.34. This suggests IP8's movement imagery is more vivid than their visual imagery, but it is difficult to say for certain without further investigation. The PSIQ was scored all high, with one 10.00, or hyperphantasia-level score, for appearance Q1: friend. The taste modality in the PSIQ was rated the highest and sound lowest, with the sound modality only scoring a moderate level overall mean. Again, it would be interesting to understand more about IP8's background with respect to the questionnaire, for example, if they had any musical training that would counter that musicians perform better in auditory imagery questionnaires than non-musicians (Bensafi *et al.* 2012).

Another participant with less consistent responding in their questionnaires, as per the graphs in Figure 3.9, is IP9, a researcher in engineering design. Both the VVIQ and VMIQ results were of moderate level imagery vividness with both resulting in an overall mean of 3.25. Further, the VVIQ responses were identical between eyes open, and eyes closed, suggesting no difference in imagery vividness for IP9 with their eyes being open or closed. In addition to this, over 95% of VMIQ responses were a 3.00 or a 4.00, showing consistency, and none of the VVIQ or VMIQ questions were rated at the extreme scores of 0.00 or 5.00. Despite this, the PSIQ overall mean was a very high-level vividness score, with over 40% of the questions rated at 8.00 (very high). There were a handful of outliers but mostly consistently high scoring, even amongst the appearance questions, despite the VVIQ and VMIQ results

showing moderate-level imagery vividness. This raises queries about the questions themselves and the impact they may have on individual responses to the questionnaires.

Comparing the participant results for the VVIQ and VMIQ, it is clear to see the consistencies in the scoring. From the graph in Figure 3.10, it is evident that while there are variations between individual participants, each participant shows good consistency among their own responses. The VVIQ means range from 1.00 to 4.75, with an overall average of 3.17, moderate-level imagery vividness, while the VMIQ has an overall average of 3.28. For both questionnaires the most obvious differences are between IP3 and IP4, and IP6 with IP3 and IP4 scoring absolute 1.00s across their questions compared with IP6's very-high level scores, indicating the varying experiences of visual mental imagery in individuals. A PCC was calculated between the scores for the VVIQ and the VMIQ resulting in a strong positive correlation of 0.967. Due to the nature of the VVIQ and VMIQ focusing on visual imagery, it is unsurprising that they would result in strong positive correlations between participant answers, suggesting that higher imagery vividness responses in one lead to higher imagery vividness responses in the other.

The PSIQ returned less consistent results among participant means, both between participants and within their individual questionnaires by modality. Figure 3.11 shows the participant overall means for each modality and clearly highlights this lack of consistency. While a participant may have a very high overall mean for one modality, they may have a lower mean for another, for example IP3's appearance modality responses were all 1.00, while results revealed high imagery vividness for the sound modality. Looking at appearance specifically, the mode is 0.00 despite returning an overall mean of 6.85 (moderate-level vividness) and a standard deviation of 3.23, showing the large variations in individual participants. Over 50% of the responses were of the extremes of 0.00, 9.00 or 10.00, while the mid-range ratings of 1.00 to 6.00 accounted for only 20% of the total responses, evident in Figure 3.11. The PCC calculations between modalities, found in Table 3.1, were all positive, with the highest being for appearance versus smell at 0.9825, and the lowest for sound versus smell at 0.5622. This suggests that generally, higher imagery vividness reported in one modality means higher imagery vividness reporting in other modalities, but there are exceptions to this, such as IP3. When comparing the PSIQ to both the VVIQ and VMIQ through PCC calculations, all calculations returned strong positive correlations, seen in Table 3.2, suggesting higher vividness in one questionnaire means higher vividness in another,

although, again, IP3 is a clear outlier. Finally, PCC calculations were undertaken comparing the VVIQ and VMIQ to the appearance modality in the PSIQ, again resulting in strong positive correlations of 0.9902 (VVIQ versus PSIQ-A) and 0.9644 (VMIQ versus PSIQ-A).

All participants responded with similarly low MRT times for questions up to Q6, then the timings jumped significantly. IP7 is a potential outlier for Q6 due to their strikingly high time, but it is not known for certain what the reason for this was. Comparing the MRT with the three imagery questionnaires, VVIQ, PSIQ and VMIQ through PCC calculations allows for an understanding of how participants respond to testing. The PCCs were lower than for other calculated correlations, but all still positive, with the lowest being the PSIQ versus MRT at 0.4020. The suggestion here is that high vividness leads to a higher average MRT time, which translates to high imagery vividness resulting in a longer time to respond to a MRT question. Investigations into the potential reasoning for this would be interesting given that it appears that low visual imagery vividness, or aphantasia, correlates with participants being faster at mental rotation tasks.

Finally, having the participants complete the SOP questionnaire attempted to provide an understanding of their style of processing and whether they process verbally or visually. There was clear variation in most participants SW versus SP scores, even amongst those where the responses led to similar means, suggesting differences in processing styles, and cognition. Interestingly, IP3, IP4 and IP5 all scored lower means on SP rather than SW leading to the suggestion that aphantasia or low imagery vividness in the visual category leads to a stronger verbal processing style. The PCCs calculated between SP and SW were all positive correlations, which is intriguing as it suggests that stronger SP scores led to stronger SW scores. The VVIQ, PSIQ and VMIQ were compared with both the SP and SW scores through PCCs, returning all positive correlations, with stronger correlations between the imagery questionnaires and SP. It is evident that stronger imagery vividness, particularly in the visual modality, is equated to stronger visual processing styles in participants. Most interestingly are the PCC calculations between the MRT versus SP and SW. As seen in Table 3.4: while MRT versus SP returned a positive correlation of 0.3766, MRT versus SW returned the only negative correlation of -0.1245. The understanding here with the low correlation calculated is that no true correlation can be determined between the MRT times and the SW processing style.

3.3 Interview study

3.3.1 Methodology

The interview study was developed to further understand the mental imagery experience of participants working in various creative industries. The study used an adapted form of coding analysis and will be qualitative in nature. The analysis was based on what the participant says during the interview, with items of note highlighted, alongside connections between key research topics. By focusing on designers in industry or those in a research career, it is expected that a deeper insight will be gained into their individual experiences and to determine a research focus for further investigations. The literature review revealed that often experienced designers are almost indifferent to their own mental imagery use (Pearson 2007; Casakin and Kreitler 2011), with many experienced designers reporting that they do not use imagery in their design work at all (Dahl, Chattopadhyay and Gorn 2001). With the additional knowledge that experienced designers tend to think faster than students, leading to connections being made with prior knowledge and experience (Gero and Milovanovic 2020), it is intriguing to consider what connection career stage has with overall mental imagery experience in design. The study was undertaken simultaneously with that in Chapter 4 to provide knowledge expansion of both sides of the career timeline: industry-level, and students.

Five of the participants from the investigation into psychometric questionnaires detailed in Chapter 3.1 were further interviewed about their experience of mental imagery while working in a design field. This includes two designers from industries other than engineering design who have high imagery vividness levels according to their questionnaires and indicated they would be interested in a discussion about their experience. These are IP1, the graphic designer, and IP2, the civil engineer with experience in engineering design. In addition, IP3, IP4 and IP5 from Chapter 3.2, all researchers across design and mechanical engineering fields, and all reporting engineering design experience, have been interviewed: these three participants responded to a call to participate reporting visual aphantasia. The three participants reported varying levels of multisensory aphantasia, but full visual aphantasia. The impact of response bias was considered at this stage to account for the participants' own desire to share their experiences and their knowledge of the research topic, but the risk was deemed negligible compared to the wealth of knowledge that could be gained from the conversations.

The interviews were conducted in Autumn of 2022, with one being held in person, and four held on Microsoft Teams. All interviews were recorded and transcribed, with

questionnaires completed beforehand to allow participants a base understanding of their own mental imagery experience, and to avoid the researcher over-explaining the experience. As before, consideration was given to the risk of response bias or socially desirable responding but again deemed less impactful than if the researcher explained the interview topic verbally. Interview topics were prepared, as can be found in the researcher notes in Appendix 3, but the format of the interview was largely casual, with open prompts. This enabled conversation to flow around the participants' responses, allowing for better insight on the topic of mental imagery. While it is acknowledged that a higher number of interviews would have generated broader insight, the knowledge gathered was supplementary to clarify the results of the questionnaire study. Combined with the questionnaire analysis in Chapter 3.2, and the study detailed in Chapter 4, the information provided insight into the real-life mental imagery experiences of individuals and corroborates the literature review in Chapter 2.

The interview transcripts were coded according to a coding scheme that was created using key findings from the literature review. The coding activity in this study allowed for an initial understanding of how the coding process works and the benefits for future research. The full coding scheme can be found in Table 3.5 and was made up of six main codes: mental imagery understanding, dimensional ability, imagery processes, modalities of imagery, imagery in design, and specific mentions of the individual's work or experience. Interview transcripts were segmented and coded twice for consistency. The coded segments were totalled and any linked codes noted to find connections between the key viewpoints. Network graphs were created to show linked elements, with numerical values, to allow for a visual interpretation of these connections. As this research was qualitative in nature, including a visual representation of the data allows for confirmation of understanding, as found in Figure 3.12 and consisting of noted links found in coding round one only (represented by pink links), coding round two only (yellow links) and those that corresponded to both rounds (black links).

No statistical analysis has been undertaken on the coded data, and no inter-participant comparisons have been made. The analysis for the study will be purely qualitative in its approach to understanding the experience of the individual participant. This is particularly important for those participants reporting aphantasia in design. As found in the literature review, mental imagery is a diverse experience (Kavakli and Gero 2001), meaning that insight into how it is experienced by specific individuals is advantageous when the goal of the research is to better appreciate the subjective nature of the experience. Finally, the outcomes for the

study are intended to increase insight into the literature research and the connections between key elements, the individual experiences of mental imagery, and how individuals discuss said experiences.

1: Understanding	1A	Neurobiology
	1B	Psychology
	1C	Cognitive ability
	1D	Subjectiveness
2: Dimensional ability	2A	Vividness
	2B	Spatial
	2C	Rotational
	2D	Perspective
	2E	Colour
	2F	Multitasking
3: Processes	3A	Generating
	3B	Combining
	3C	Memory
	3D	Imagination
	3E	Daydreaming
	3F	Styles
	3G	Behaviours
4: Modalities	4A	Visual
	4B	Auditory
	4C	Tactile
	4D	Olfactory
	4E	Multisensory
	4F	Emotion
5: Design	5A	Processes
	5B	Methods
	5C	Tools
	5D	Awareness
	5E	Intention
	5F	Inspiration
	5G	Design changes
	5H	Design fixation
	5I	Communication
	5J	Teamwork
	5K	Processing
6: Specific	6A	Personal view

Table 3.5: Interview study coding scheme

3.3.2 Results and analysis

IP1

IP1 is a graphic designer with seven years industry experience at a small, privately-owned graphic design company. Their transcript coding was made up of 69 total coded segments, with 36 of these receiving inter-code connections. IP1 had a very low number of segments coded with code six (referencing their own work specifically), and the only code connections that were missing from their overall numbers were those connected with six. This suggests there was little to no discussion of their own work experiences that were relevant to their mental imagery experience. It is highlighted that IP1 also told the interviewer that their design work is heavily reliant on on-screen designing which they felt removes part of their need for imagery use. They described it as a reduced need to trial designs and design features in their own head. This indicates a potential lack of correlation between IP1's mental imagery experience and their work as a graphic designer.

While IP1 did not discuss their own work experience, there was an overwhelming emphasis on the discussion of their mental imagery processes, and some high levels of discussion for the other coded elements. Some points of interest are that they described sound imagery as being "easier", which may be linked to their training as a musician, and their high sound imagery vividness levels shown in Chapter 3.2's questionnaire responses. IP1 also told the interviewer that they found imaging tasks that they do not experience regularly or daily harder, which will be interesting to consider in future studies and if this is a cause for lower vividness scores on certain questions. There was an interesting discussion on the rotation questionnaire experience, with IP1 detailing that they found the task difficult, potentially due to their education. They explained that they were trained in art school to look for the negative shape in an object, which led to them overanalysing the rotation task by trying to look at it from an artistic perspective, providing potential evidence of the impact of prior training on mental imagery experience.

The network graph for IP1, seen in Figure 3.12, clearly depicts a large number of connections between the discussed viewpoints, with approximately 50% of the coded segments featuring connected codes. The exception for this is code six, which can clearly be seen to have no connections, as discussed previously. In addition, there were triple-way connections between codes one, two and four, and codes two, three and five, suggesting more intricate levels of connections between the viewpoints found in Chapter 2. Finally, IP1 also

stated that “the idea of not being able to imagine something wouldn’t really make sense to me” which, when compared with their imagery questionnaire responses, indicates an awareness of their high-vividness level mental imagery experience.

IP2

As a refrigeration engineer with a civil engineering background, IP2 reported a large amount of experience in engineering design. Their coded transcript segments totalled 102, with 63 of these for connected codes. There were no connections between code one (understanding of mental imagery) and the other codes during the second round of coding, which suggests a change in researcher assumption on how the participant is describing the understanding they have of their experience. As with IP1, IP2’s interview featured a lot of discussion around imagery processes, as well as their design experience, and overall returned consistent coverage of the coded elements. The network graph, found in Figure 3.12, revealed many connections for the first round of coding but less for the second. Overall, there was a variety of connections with approximately 50% of segments coded with two or more codes. Additionally, IP2 returned triple connections for two, three and four, suggesting that their description of their mental imagery experience ranged across different elements.

IP2 stated that they were aware of experiencing or utilising mental imagery which may explain their ease at discussing what is happening within their mind. Additionally, they noted that their spatial awareness, they feel, is highly based on memory, with an example being that they are uncomfortable driving somewhere without knowing the street plan, as they are unable to visualise the world around them. This is an intriguing point and a connection that had not been considered by the researcher previously. In terms of their engineering career, IP2 made a few points that were highlighted as interesting, including that engineering is largely about optimisation, so they find they use knowledge a lot more in work. This is expected for an engineering designer given the prior research by Dahl, Chattopadhyay and Gorn (2001) and suggests there is less room for innovation in industry. IP2 also claimed they find it frustrating working in a team at times because their mental image during their idea generation role might not be what someone in the next stage of the design process sees or manufactures from the specifications. This is another interesting potential point of research, particularly when considering designers with diverse mental imagery experiences. Finally, they made clear several times that they relied heavily on imagination when they were a student or at the start of their industry career, whereas now they have a “back catalogue of images and examples and

things that I've done that have or haven't worked". This supports research by Gero and Milovanovic (2020), amongst others in the literature review, that there is a difference between novice and experienced designers, while also leading the researcher to consider if focusing on students would allow for more wide-ranging insight of the mental imagery experience during the design process to ensure there are fewer external influences on their experience of design process.

IP3

As can be seen in Chapter 3.2, IP3 has reported total visual aphantasia, which was the focal point for their interview. Their transcribed interview featured 79 coded segments, 45 of which featured connected codes. They had fewer connections for codes one, five and six, indicating a higher conversational focus on the elements of the mental imagery experience, rather than the overall understanding and their real-life application. However, code five was coded regularly as a single code, which may indicate a potential oversight in considering mental imagery in their design experience. IP3 also discussed dimensions of imagery a lot more than other elements, which is unsurprising for someone reporting visual aphantasia, as their interview focused heavily on this element. As seen in Figure 3.12, IP3's network graphs again show more connections for the first round of coding, but overall, a very connected network. Again, IP3 had over 50% of their coded segments as connected codes, and returned triple connections on one, two and three, one, five and six, and two, three and four.

There were many insights in IP3's interview data, largely relating to their reported aphantasia. One example is quoted below:

"I was chatting to someone earlier who said when he designs stuff, he's got very vivid mental imagery. So, he said, for example, he was looking at a mug and he can, in his mind's eye, take the mug, cut it down the middle, colour all the sections, and then cross section. He can do changes there and then. So, comparing that to how I would do it, which is much more that I know what operations could be successful. So, for example, if the handle wasn't large enough, I'd think, OK, I need to make the handle larger. I wouldn't be able to visualise it, but I could know what process I'd need to do in CAD or on paper to try and enlarge it visually to see."

This example of being unable to access the same internal design skills as a colleague is an intriguing potential research focus on the impact that cognitive diversity in terms of mental imagery has on an engineering designer's ability to complete a task. Bilda and Gero (2008),

found that designers frequently find themselves solving design problems outside of the design space through their ability to visualise the problem in their mind's eye. This point from IP3 suggests that designers with aphantasia have no access to this element of the design space, and it would be interesting to understand if they have alternative ways of working or what impact this has on their design process.

Other points of interest in IP3's transcript are that they discuss their use of computer aided design (CAD), with specific focus on it acting as a substitute for their inability to visualise in their mind. This may correlate with IP1's statement that their computer design requires less use of their mental imagery, a sentiment backed up by IP3's viewpoint of computer design requiring less imagination. While there is a large amount of research on mental imagery and its connection with sketching, it would be beneficial to understand the connection with other design methods and tools. This would be especially interesting considering that IP3 appears to blame mental imagery for their being "bad" at sketching, so it is possible that other design methods and tools are an alternative. Finally, IP3 stated that they felt "bitter" when they first discovered aphantasia, and that they were missing out on something. These negative emotions should be considered in future research, to ensure a sensitivity to any individuals displaying or reporting this cognitive diversity.

IP4

As an aerospace engineering researcher, IP4 made clear that they have worked on several design projects and have a good amount of engineering design experience. Their transcript featured 71 coded segments, 40 of which were connected codes. They had a number of missing connections, and there was no mention of code six at all in their transcriptions. Additionally, code one featured a low number of connections. Despite this code one, and code four, were the most frequently discussed elements during the interview, which may align with their attempt to understand what aphantasia is and how it impacts them, having recently learned about the phenomenon. Further, IP4's network graphs, Figure 3.12, highlighted the low variation in the connections, but with 50% of the coded segments featuring connected codes, it appears that there were limited connected elements, and less variation among connections. IP4 also returned triple connections of one, two and four, one, three and four, one, three and five, and one, four and five.

IP4's questionnaire responses in Chapter 3.2 stood out due to their reporting of complete visual aphantasia, as well as extremely low imagery vividness across all other

modalities. As with IP3, IP4 claimed they are “bad” at drawing and appeared to suggest a connection between their aphantasia and their sketching abilities. During the interview, IP4 seemed to be attempting to grapple with the discovery of aphantasia, and that they might be missing out on an experience other individuals are having. One particular moment to highlight is their claim that “I can’t remember my girlfriend’s face, like there’s absolutely nothing going on, it’s slightly distressing.” This, again, highlights the importance of sensitivity when dealing with research on cognitive diversity to ensure that participants’ emotions are respected.

IP5

IP5 is a researcher in the same team as IP3 and IP4 and had also recently discovered they have potential visual aphantasia. IP5’s transcript returned 106 coded segments, with 62 of these connected. As with IP4, there were a lot of missing connections and no mention of code six at all, plus low connections with codes four and five. This is interesting as it shows a focus on understanding the mental imagery experience and that process and dimensions featured heavily in the interview. Codes one and two were the most frequently discussed, which, again, could be connected to IP5 coming to terms with understanding aphantasia and his own mind. IP5’s network graph (Figure 3.12) revealed similarly low connections to IP4, but in the same manner, the connections made up over 50% of the coded segments so it is likely, again, that there was less variation in type of connection. Finally, IP5 returned triple connections of one, two and three, one, two and four, one, two and five, and one, three and five.

An interesting point highlighted by IP5 is that they claimed to have always assumed they have bad memory, when they are now considering that aphantasia could be the cause. IP5 also had interesting ways to describe their sketching ability, such as their claim that they have no mental image whilst sketching, with their mind feeling almost blank during the activity. The most interesting point to note is that they described seeing a mental imagery as being akin to their peripheral vision. IP5 stated that they can see a mental image but as soon as they focus on it, it disappears; it appears to only occur when they are unaware or unfocused on the cognitive task specifically. This has intriguing research connotations for imagery intention and how aphantasia is measured. This signifies not full visual aphantasia but something “other” that is not considered in the traditional psychometric questionnaires, such as the VVIQ. Furthermore, it provides additional evidence to the understanding that mental imagery

experiences differ between individuals and at least a partially qualitative approach is needed to fully understand the range of experiences.

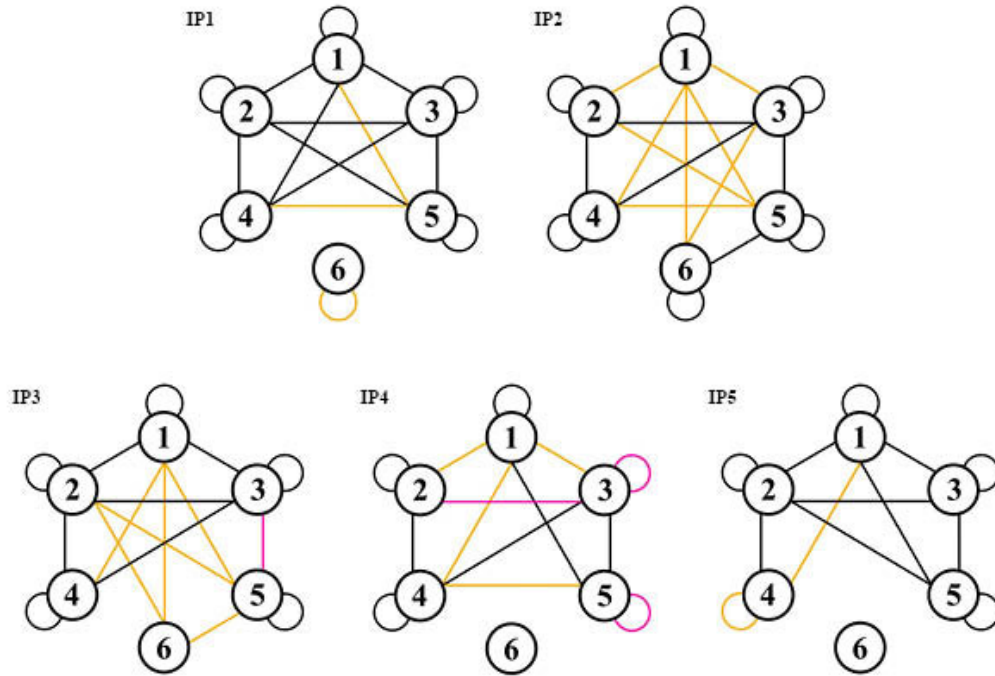


Figure 3.12: Network graphs as segmented by the coding scheme in Table 3.5

3.4 Conclusion

The work in this chapter follows on from the literature review in Chapter 2 and the researcher's holistic understanding of mental imagery experiences, acquired through casual conversations that included individuals claiming they "see" their imagery in front of them, or that they only visualise words. From the psychometric measurement questionnaire responses detailed in Chapter 3.2, the variation in the experience of mental imagery is evident and there are some key findings of note. Firstly, is that there is some impact of the question being asked, and while this appears to not be an issue for all participants, there are some individuals who struggled with particular topics, such as IP2 who stated they struggle with visualising faces. It was further confirmed during the interview study by IP1 making clear that they struggle more with questions that ask them to visualise something they are less familiar or have less experience with. This suggests that the limited nature of the psychometric questionnaires being set topics may be misrepresenting an individual's mental imagery experience as it is not

personal to them. Additionally, while there is a great deal of variation between participants, the mental imagery reported by each participant is consistent among their own cognition. In terms of multisensory imagery, evidence supporting Bensafi *et al.*'s (2012) research findings that musicians report higher sound imagery than non-musicians can be found from IP1's responses to the questionnaires, and IP4's responses show potential multisensory aphantasia, both of which are possible areas for future research. For the questionnaires themselves, it has been decided that the VVIQ and PSIQ are the most appropriate for investigation in this research project: the VVIQ due to its simplicity of use for reporting the visual mental imagery experience, and the PSIQ as it measures multisensory imagery in a consistent manner. One area of possible contention to note is the lack of consistency in measurement systems between questionnaires, with systems ranging dramatically between questionnaires. The use of a "1" rating to measure aphantasia in the VVIQ and VMIQ adds additional confusion as it contradicts the description of "no imagery".

Despite any issues, imagery measurement questionnaires are useful when measuring the mental imagery experience, and the statistical analysis of the questionnaire responses provides evidence of this usefulness at finding intricate differences in designers' experiences. However, when considering mental imagery in design, general use questionnaires appear to be missing a situation-specific element. Taking the PSIQ for example, while it is useful for understanding designers' mental imagery experiences in a multisensory domain, a more useful questionnaire would ask if and how they experience multisensory imagery in design-specific situations. A design-specific questionnaire would allow the measurement of such an experience, hypothetically providing greater insights into elements of the mental imagery experience in design, such as how designers work alongside their imagery, to find correlations between designers, design work and mental imagery. While the results provide evidence of diverse mental imagery experiences, since the questionnaires are not specific to design, it is difficult to determine how these experiences translate into the design process. Additionally, the general focus for mental imagery measurement questionnaires is to measure the experience through the dimension of vividness. The literature review in Chapter 2 makes clear that the individual experience of mental imagery features many more elements, such as the differences between memory and imagination imagery (Rhodes 1981; Dahl, Chattopadhyay and Gorn 1999; Dahl, Chattopadhyay and Gorn 2001; Pearson 2007; Pearson 2019). It is theoretically possible to create a measurement system that fully encompasses the entire experience of

individual mental imagery in design, but further research is required on inclusions and how this would be undertaken.

In terms of qualitative findings from the designers' insights, there were many interesting elements that were discussed, including the use of on-screen design work impacting on mental imagery. IP1 stated that they use less imagery in their work because they regularly use screens for their design work, while IP3, IP4 and IP5 all reported visual aphasia and claimed to utilise CAD a lot more in their design work as they claimed to find it easier when they are not visualising. This potential correlation between the two extremes of imagery experience is interesting as it suggests a workaround to the cognitive diversity created by varying experiences of mental imagery: CAD allows a designer more freedom with their design work when they do not have a visual image in their head to manipulate. Additionally, it was queried whether higher imagery vividness leads to higher utilisation of mental imagery in the design work. However, with the knowledge of the impact of screens and how prevalent they are in design now, and that professional designers, including IP2, claim to use more memory than imagination (Gero and Milovanovic 2020), it leads the researcher to ponder if this is dependent on the situation: whether there is a difference between imagery utilisation in a designer's personal life versus their professional experience. Further, IP5 suggested that their mental imagery is only apparent when they were unfocused, which would be an engaging point of further research. Finally, there were a few impactful observations that supported the need to consider cognitive diversity in terms of mental imagery experience: IP2 stated they find it frustrating working as a team due to other team members not sharing the images IP2 sees in their own head; IP3 made clear they are unable to access an internal design space while their colleagues can; and all three participants who reported visual aphasia made a negative comment in some form about missing out because of their lack of mental imagery. These make clear that the consideration of mental imagery diversity is important in this research and should be approached with care for any participants involved.

3.5 Summary

To summarise, this chapter details an investigation into the use of psychometric self-response questionnaires to measure mental imagery experiences alongside a series of interviews with industry-level designers across various fields. The study follows on from the literature review detailed in Chapter 2 and provides insight through dialogue within a

controlled environment into the experiences of mental imagery and how these can be translated to research. The chapter enabled a first-hand understanding of the diverse experiences of mental imagery in creative professionals to be developed and positions real-life experiences alongside the literature findings. The diverse experience of mental imagery was documented through the questionnaire responses and conversations, whilst providing evidence that self-reporting of mental imagery allows the necessary insights and highlighting the need for dialogue when building understanding of the unique mental imagery experience of an individual.

Chapter 4: Preliminary study on design, emotion and mental imagery

4.1 Introduction

4.1.1 Research aim

The literature review, detailed in Chapter 2, identified that there are intriguing connections between mental imagery and emotion (Taruffi *et al.* 2019; Ji *et al.* 2022) and a gap in the context of engineering design. Chapter 3 has a focus on mental imagery in experienced designers, and an opportunity arose to understand how novice designers could be better supported. This led to the assumption that engineering design students will perform better in a design module with an emotion theme if they report having more vivid mental imagery, and that by undertaking a first-hand investigation of the complex connection between emotion and mental imagery the researcher would gain deeper insights on the topic. By comparing engineering design students' responses to a psychometric questionnaire measuring mental imagery vividness to their achieved grade, the outcome of this investigation was an understanding of the impact their mental imagery experience has on their grade outcomes. Quantitative data was analysed using statistical analysis techniques and to calculate a PCC.

4.1.2 Research approach

The approach to this research study was as follows:

- Validate the approach by conducting a pilot study.
 - Students completed an online questionnaire that features the PSIQ (Andrade *et al.* 2014).
 - Student module outcomes (grades) were collected.
 - The data was compared to understand if there is an indication of a correlation between mental imagery and grade achieved.
- Reflect if the outcomes of the pilot enable conclusions to be drawn.
 - Determine the success of the investigation against the research assumptions.

- Repeat if and as necessary to ensure confidence of the results.
- Reflect on the outcomes of the research.

Positive correlations should be determined between the students' PSIQ responses and their overall module grades to confirm if the assumptions about module success and mental imagery vividness were correct. PCCs were calculated between different modality responses on the PSIQ, and the vividness scores versus the module grades. This had the additional benefit of allowing pilot analysis to remove any unnecessary information and make changes to the process if and where needed. While success of the research was determined by any clear correlation, be it positive or negative, a significant lack of correlation between data points would be an unfortunate failure to find any meaningful results.

4.1.3 Design Emotion and Experience module

The Design Emotion and Experience module (DM300) at the University of Strathclyde's Department of Design, Manufacturing and Engineering Management (DMEM) is undertaken by third year students studying undergraduate Product Design and Innovation (PDI), Product Design Engineering (PDE), and Sports Design Engineering (SDE). The module involves a design project concerned with design form and aesthetics that emphasises the importance of emotion and experience in design. The module was appropriate as a focus of this research for the following reasons:

1. It has a unique attention to emotion within design, placing emotion and experience at the centre of the design process.
2. It is a third-year module meaning that the students involved will have at least two years of engineering design experience.
3. The module is assessed through one design project that the student embarks on as an individual from the initial research stage, right through to detailed design and prototyping. By using an individual project, rather than a group project, the number of variables is reduced, and each student is placed on a relatively equal level academically.
4. The project is to design and develop a speaker which, in theory, utilises at least three senses: sight, sound and touch, as well as emotion.

4.2 Methodology

For the research study, students in the module were asked to opt-in to participating and to provide student numbers in order to link their module grades with their PSIQ responses in order to ensure anonymity, which was explained to the participants alongside data management procedures and ethical considerations. Participants were emailed a link to an online version of the PSIQ and were asked to complete all parts within two weeks. The results were analysed individually with statistical analysis, then compiled and analysed as the entire group of participants. Once the grades for their final project were confirmed, these were used to compare how vivid their perceived imagery was to how well they performed in the module using statistical analysis and PCCs. Data was collected but there was no unnecessary personal information involved, and any personal information was used solely for identification purposes of each participant to ensure the correct grades and PSIQ responses are kept together. The PSIQ is a psychometric questionnaire but does not require any strenuous or taxing effort to complete and is not asking participants for any sensitive information. Consent was obtained from all volunteer participants, and they were advised that they could withdraw consent at any time as participation was entirely voluntary.

13 students initially signed up and 11 returned their PSIQ within the allocated time frame. Of these 11, one was removed from the study after failing to complete their project on time resulting in a zero grade for the module. Three of the final ten participants were on the PDI course and seven were on the PDE course. No other additional identifying information was requested from the students. The questionnaire was emailed to participants, and they were advised to undertake it in a quiet and alone. It was decided that setting is not impactful on this research, removing it as a potential variable.

The PSIQ is a self-response psychometric questionnaire developed by Andrade *et al.* (2014), as detailed in Chapters 2 and 3. It features seven sections, each with five questions, and measures mental imagery vividness on a scale of 0-10 for appearance, sound, smell, taste, touching, bodily sensation, and feeling. Imagery is measured through descriptors that relate to the average scores on the PSIQ. The PSIQ is measured on a 0-10 scale, and so imagery is described in this chapter using the following breakdown of result (r):

$r < 1$ = possible aphantasia

$1 < r < 2.50$ = very low imagery vividness

$2.5 < r < 3.5$ = low imagery vividness

$3.5 < r < 6.5$ = moderate imagery vividness

$6.5 < r < 8$ = high imagery vividness

$8 < r < 9.5$ = very high imagery vividness

$r > 9.5$ = possible hyperphantasia

The DM300 module is graded in two submissions: a critique at week 6, and the final project submission at week 11. The final submission has two grades for the exhibition (consisting of the final design and presentation), and for the journal that students are expected to keep throughout the entire project. The critique makes up 15% of the overall grade and was deemed unnecessary to consider on its own. The remaining 85% is split between 65% for the exhibition and 20% for the journal, each graded out of 100 total. The exhibition grade is split into five equal assessments, each out of 20:

- Level of aesthetic definition
- Precision of final design form through 3D modelling (digital and physical modelling)
- Integrity of experience design
- Quality of visual and made communication
- Level of critical thinking

The journal grade is split into two assessments, each out of 50:

- Expression of reflective critical and individual approach to project
- Engagement with emotional design and experience design topics and readings

The assessment criteria can be found in Appendix 4. The overall grade is calculated as follows:

$$(\text{Critique grade} \times 0.15) + (\text{Exhibition grade} \times 0.65) + (\text{Journal grade} \times 0.20)$$

The PSIQ responses and the final grades were analysed using statistical analysis. This included calculating the mean, mode, median, quartiles, range, standard deviation, and

variance of the overall scores per modality for each participant, each participant grade and overall module result, the overall PSIQ results per modality for the entire set of participants, and the breakdown per question for each modality. Further to this, PCCs were calculated for the following sets of data:

- Module results comparing critique, exhibition, journal and overall grades
- PSIQ responses per modality
- PSIQ vs. critique, exhibition, journal and overall grades
- PSIQ vs. exhibition breakdown grades
- PSIQ vs. overall and exhibition breakdown grades per each question

4.3 Results

The PSIQ results revealed a variation in the experiences of mental imagery across the ten participants. The full table of response scores can be found in Appendix 5. When considering responses to any question in any modality, less than 3% of participant responses were a score of less than 4.00 (“low” vividness), 30% of responses were in the “moderate” vividness range, almost 56% were scored “high” or “very high” vividness, and over 11% were scored 9.50 or above (“potential hyperphantasia”). Additionally, 5/10 participants’ overall mean result was “high” vividness, 3/10 were “very high” vividness, and 2/10 were “moderate” vividness. No participants returned an overall mean score of less than “moderate”, or 5.20. The overall mean results can be found in Table 4.1. The overall variance for all responses was 5.20 which confirms the medium-level variation seen in individual responses. The overall module mean by modality scores were all “high” vividness scores of 6.56 and above, except for the appearance class mean which was 8.04 (“very high” vividness). The overall module mean for all responses was 7.17, or “high” mental imagery vividness. Furthermore, the overall module mode and overall module median response were both 8.00 (high vividness results). The full participant means by modality can be found in Table 4.2.

Participant	Mean
1	6.86
2	7.54
4	8.46
5	7.77
6	4.77
7	8.31
8	7.31
9	5.63
10	7.00
11	8.00

Table 4.1: Overall participant mean PSIQ scores for all modalities

Participant	Appearance	Sound	Smell	Taste	Touching	Body	Feeling
1	8.40	6.20	7.40	6.60	5.60	5.20	8.60
2	7.80	7.00	8.20	8.40	9.60	8.40	3.40
4	8.80	7.00	8.00	8.00	9.00	8.80	9.60
5	9.80	6.60	7.80	8.40	9.00	7.40	5.40
6	3.60	5.00	2.20	6.00	5.80	5.20	5.60
7	9.80	9.60	6.60	9.00	9.40	6.60	7.20
8	8.00	8.00	8.40	7.00	7.00	5.60	7.20
9	6.00	5.20	6.00	5.40	5.60	4.20	7.00
10	8.20	6.40	8.00	5.80	6.80	6.80	7.00
11	10.00	9.80	6.80	5.80	10.00	7.40	6.20

Table 4.2: Participant mean PSIQ scores per modality

The PCCs were calculated to compare the results by modality. Each modality was compared to each other by participant to find correlations. All calculations, excluding any involving the feeling modality returned positive or strong positive correlations, with appearance versus smell being the highest at 0.7507, and sound versus smell the lowest with 0.3710. The feeling modality correlations are more variable and weaker: feeling versus appearance at 0.1836 and feeling versus smell at 0.1597 were both positive correlations, feeling versus sound at 0.0342 was a weak positive correlation that is almost negligible, feeling versus taste at -0.1202, bodily sensation at -0.1413, and touching at -0.2757 are all negative correlations. However, with all feeling results, the data appears clustered, rather than a clear correlation and so it is difficult to garner a definitive result. All PCCs can be found in Table 4.3.

<i>Pearson</i>	<i>Sound</i>	<i>Smell</i>	<i>Taste</i>	<i>Touching</i>	<i>Body</i>	<i>Feeling</i>
<i>Appearance</i>	0.7456	0.7507	0.4925	0.7008	0.5645	0.1836
<i>Sound</i>		0.3710	0.3721	0.7375	0.4140	0.0342
<i>Smell</i>			0.3825	0.4062	0.4930	0.1597
<i>Taste</i>				0.6417	0.5928	-0.1202
<i>Touching</i>					0.8461	-0.2757
<i>Body</i>						-0.1413

Table 4.3: Pearson correlation coefficients between modalities

The overall module grades can be seen in Table 4.4. PCCs were calculated to compare the participants' responses to the PSIQ with their module grades. The participants' mean per modality and overall mean scores in the PSIQ were compared with their overall module grades, their exhibition and journal grades, and with their exhibition breakdown grades. Almost 85% (54 out of 64) of the PCCs calculated were negative correlations and the PCC for the overall means versus the overall grades was -0.4288. Of the PCCs calculated for the overall grade, three of the seven modalities gave similar negative correlations (smell, touching and bodily sensation). Appearance versus the overall grade had a correlation of -0.5343 and taste of -0.5861 which are both strong negative correlations. The sound correlation with the overall grade is weak at -0.0308 and almost negligible. Again, the feeling modality is an outlier with a positive correlation at 0.2605.

The PCCs calculated for the PSIQ compared with the exhibition and journal grades were similar, with the overall exhibition at -0.4977, and the overall journal -0.3303. The PCCs for appearance versus exhibition, smell versus exhibition and taste versus exhibition were all strong negative correlations, with the lowest being for taste at -0.6153. The sound modality results were more variable with sound versus exhibition at -0.1432 and journal at 0.0327, however, both are almost negligible correlations. The feeling modality PCCs were positive for both exhibition and journal at 0.1526 and 0.2330 respectively.

The exhibition grade breakdown followed a similar pattern with mostly negative correlations. The PCCs found for the overall PSIQ means were all negative or strong negative results with the lowest being the precision score at -0.5886, and the highest being quality at -0.2977. Again, appearance, smell and taste are all negative correlations. Sound, touching and bodily sensations have some variation, with sound having two weak positive correlations with experience (0.1134) and thinking (0.1086), touching having one weak positive correlation with thinking (0.0586), and bodily sensations having two weak negative correlations with quality

(-0.0045) and thinking (-0.0654). Feeling was variable with precision, experience and quality all positive correlations (highest 0.3297 for quality), aesthetics weak positive (0.1415), and thinking negatively correlated (-0.2182). The full table of PCCs can be found in Table 4.5. Visual representation of the overall PCC between PSIQ overall mean score and grade attainment can be found in Figure 4.1.

Participant	Overall
1	65.60
2	63.85
4	70.20
5	55.90
6	77.35
7	68.40
8	74.35
9	70.15
10	73.05
11	71.40

Table 4.4: Overall DM300 module grades attained

Pearson	EXHIBITION	JOURNAL	OVERALL
Appearance	-0.6051	-0.4752	-0.5343
Sound	-0.1432	0.0327	-0.0308
Smell	-0.5279	-0.2572	-0.4642
Taste	-0.6153	-0.3559	-0.5861
Touching	-0.3988	-0.3670	-0.4009
Body	-0.2979	-0.4303	-0.3596
Feeling	0.1526	0.2330	0.2605
Overall	-0.4977	-0.3303	-0.4288

Table 4.5: Pearson correlation coefficients between PSIQ and grades attained

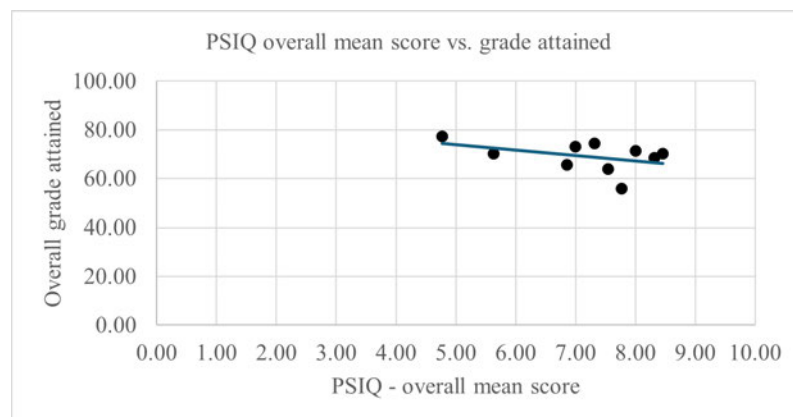


Figure 4.1: Correlation between PSIQ overall mean score and grades attained

The results were analysed per PSIQ modality to check for any outlying results of interest in the specific questions. The sound modality, the details of which can be found in Tables 4.6 and 4.7, had a few variables of note, such as participant one (p1) who scored questions (Q) 7.00, 6.00, 9.00, 7.00, and 2.00, with a range of 7.00 and no modality, and p2 who scored 9.00, 10.00, 2.00, 8.00, 6.00, with a range of 8.00 and no modality. Q3 across all participants had the highest variance with 8.18 and a range of 8.00 (2.00 being the lowest score and 10.00 the highest). The PCCs returned mostly weak correlations but with outliers, such as when comparing Q1 and Q2 to the overall grades (-0.1840 and -0.2141 respectively). Additionally, there were some positive correlations, such as Q4 versus the journal grades (0.2072). The lowest PCC was -0.5125 for Q4 versus quality, and the highest was 0.3726 for Q3 versus experience score.

Participant	Q1	Q2	Q3	Q4	Q5
1	7.00	6.00	9.00	7.00	2.00
2	9.00	10.00	2.00	8.00	6.00
4	8.00	8.00	7.00	7.00	5.00
5	6.00	9.00	6.00	6.00	6.00
6	6.00	7.00	4.00	5.00	3.00
7	8.00	10.00	10.00	10.00	10.00
8	6.00	9.00	10.00	8.00	7.00
9	4.00	6.00	5.00	7.00	4.00
10	5.00	8.00	5.00	5.00	9.00
11	9.00	10.00	10.00	10.00	10.00

Table 4.6: Sound modality responses by question

Pearson	EXHIBITION	JOURNAL	OVERALL
Overall	-0.1432	0.0327	-0.0308
Q1	-0.2344	-0.1283	-0.1840
Q2	-0.2169	-0.1735	-0.2141
Q3	-0.0349	0.1474	0.1156
Q4	-0.2342	0.2072	-0.0638
Q5	0.0288	-0.0118	0.0628

Table 4.7: Pearson correlation coefficient between sound by question and grade

Bodily sensation returned totals found in Tables 4.8 and 4.9, with p11 scoring questions 9.00, 1.00, 8.00, 9.00, and 10.00, giving a range of 9.00. Further, Q3 had a variance of 9.21 and a range of 8.00. The PCCs of the bodily sensation modality were mostly negative or strong negative, except Q3 which is entirely positive, the results of which range from 0.0336 to 0.3093.

Participant	Q1	Q2	Q3	Q4	Q5
1	8.00	8.00	2.00	5.00	3.00
2	6.00	7.00	10.00	9.00	10.00
4	9.00	9.00	9.00	7.00	10.00
5	8.00	8.00	3.00	10.00	8.00
6	7.00	5.00	3.00	4.00	7.00
7	7.00	7.00	5.00	7.00	7.00
8	4.00	5.00	7.00	5.00	7.00
9	5.00	3.00	3.00	6.00	4.00
10	9.00	3.00	9.00	8.00	5.00
11	9.00	1.00	8.00	9.00	10.00

Table 4.8: Bodily sensation modality responses by question

Pearson	EXHIBITION	JOURNAL	OVERALL
Overall	-0.2979	-0.4303	-0.3596
Q1	-0.0696	-0.5576	-0.1507
Q2	-0.5388	-0.3540	-0.5294
Q3	0.1936	0.1609	0.1824
Q4	-0.5727	-0.6935	-0.6468
Q5	-0.0500	-0.1611	-0.1142

Table 4.9: Pearson correlation coefficients between bodily sensation and grade

Feeling had many results of note, seen in Tables 4.10 and 4.11, including p11 who responded 8.00, 8.00, 3.00, 10.00, and 2.00, with a range of 8.00 and a high of 10.00. For the feeling questions, most of the results gave a high variance: Q1 with 6.68, Q3 with 7.16, Q4 with 6.68, and Q5 with 6.49. The PCCs were varied, for example Q2 returned all negative correlations while Q5 returned all positive correlations (excluding the thinking grade). The lowest PCC was -0.5283 for Q2 versus thinking, and the highest was 0.6381 for Q5 versus the journal grade.

Participant	Q1	Q2	Q3	Q4	Q5
1	9.00	9.00	8.00	9.00	8.00
2	1.00	5.00	2.00	4.00	5.00
4	10.00	10.00	10.00	10.00	8.00
5	8.00	8.00	4.00	5.00	2.00
6	5.00	4.00	7.00	5.00	7.00
7	8.00	8.00	8.00	5.00	7.00
8	6.00	7.00	7.00	8.00	8.00
9	5.00	6.00	8.00	8.00	8.00
10	7.00	7.00	9.00	3.00	9.00
11	8.00	8.00	3.00	10.00	2.00

Table 4.10: Feeling sensation modality responses by question

<i>Pearson</i>	EXHIBITION	JOURNAL	OVERALL
<i>Overall</i>	0.1526	0.2330	0.2605
<i>Q1</i>	-0.0972	-0.2598	-0.0556
<i>Q2</i>	-0.3932	-0.3090	-0.3066
<i>Q3</i>	0.3743	0.3878	0.4396
<i>Q4</i>	0.0386	0.2233	0.1450
<i>Q5</i>	0.4627	0.6381	0.5472

Table 4.11: Pearson correlation coefficients between feeling question and grade

4.4 Discussion

The results of the PSIQ were high across the board, with no aphantasic results and minimal low responses when considering the entire set of responses from all participants (seen in Table 4.1, Table 4.2 and Appendix 5). With only 3% of participants scoring any question under 4.00, and almost 56% of all responses “high” vividness or above, the data is evidently skewed to participants having more vivid mental imagery. Considering that only 3-7% of the population are believed to have hyperphantasia (Zeman 2021), 11% of the responses being “potential hyperphantasic” appears remarkably high, however this could be skewed by the small data set of only ten participants, or by the participants being engineering design students. This could also be linked to the varied participant responses, with ranges high throughout. Additionally, the overall mode and median are both 8.00 which is consistent with the overall “high”/“very high” vividness results. The overall variance at 5.20 shows a high level of variation in the participant responses, leading to further questions given the small population size.

The results by modality followed a similar trend, with the overall mean for all modalities 6.56 or above (all “high” vividness). Appearance was an outlier with a mean of 8.04 and “very high” vividness. There are a few potential reasons for this, but visual mental imagery is commonly the most discussed modality, so it is likely that has played a part in the results. To confirm this, an interview or follow-up questions on how the participants responded to each question would be useful, however, that is beyond the scope of this investigation.

There were minimal results for discussion when considering the responses by individual question. The sound modality had a few varied answers, such as p1 with a response range of 7.00 and p2 of 8.00, with neither having a mode response. Further, Q3 for sound had

a variance of 8.18 and a range of 8.00 which shows a very high level of variation in the responses for this question. The questions for sound were as follows:

1. An ambulance siren
2. Hands clapping in applause
3. The mewing of a cat
4. The sound of a car horn
5. The sound of children playing

Considering Q3 again, “the mewing of a cat” may not be a common sound in each participants’ day-to-day life and so p2, for example, who answered 2.00, may not have felt it as straightforward to perceive this sound as p7 who answered 10.00. Mental imagery is a subjective experience (Richardson 1991), which could be an explanation for the variation in responses. Presenting psychometric questionnaires, such as the PSIQ, as a one-size-fits-all solution to mental imagery measurement may be neglecting experiences of vividness by simply asking the wrong question to the wrong person. If “the mewing of a cat” is not a regular sound heard to one person, but to another it is, then that automatically presents a variable to overcome.

Bodily sensation had similar results with a variance of 9.21, and ranges as high as 9.00. The variation in results for this modality could also be attributed to the individual experiences of participants, or the understanding of what the modality is asking them to perceive. With the other five modalities, appearance, sound, smell, taste, and touching, these are straightforward in that they all represent each of the five senses, whereas bodily sensation is somewhat of an outlier. At first glance it seems like it should be similar to touch, but it is asking a more specific experience than touch alone, with participants needing to consider the way their entire body perceives the situation, making it a potentially harder experience to perceive internally. The bodily sensation questions:

1. Relaxing in a warm bath
2. Having a sore throat
3. Threading a needle
4. Jumping into a swimming pool
5. Walking briskly in the cold

vary on how detailed the image of them should be. For example, “having a sore throat” is a specific area of the body that you would feel at a specific time, while “walking briskly in the cold” would involve the sensations of walking, the cold, and moving briskly, at the same time as receiving input from every other sense, such as the visual imagery of a specific sense. These could be reasons why there is a high variation in the responses to the bodily sensation modality, and may represent a lack of relevance for a study focused on design: why ask about a swimming pool when we are gathering information on how a student designs?

Feeling as a modality is important to discuss by question as it is a more subjective experience. The results per participant were varied, as expected, with all questions returning a high variance. For example, p11 had a range of 8.00 and a high of 10.00; Q1 had a range of 9.00, and a high of 10.00. Participants were asked to “feel” the following emotions:

1. Excited
2. Relieved
3. Furious
4. In love
5. Scared

However, it is likely that any irregularities or variations in the responses are due to emotion being a more subjective experience. While “threading a needle” is a literal experience that every person would undertake in mostly similar ways, the feeling of being “in love” can differ from person to person, so it is harder to measure it accurately. This, again, relates back to the subjective nature of mental imagery and vividness measurement, with questions, such as the feeling of being “in love”, proving potentially too subjective to measure fairly and accurately.

PCCs were calculated to compare each modality across all ten participants. All correlations between modalities were positive or strong positive, except those comparing the feeling modality. These results are available in Table 4.5. The module does not involve any smell or taste experiences and so, in hindsight, it was not necessary to measure participants’ mental imagery in these modalities. The other five modalities can be argued as necessary, with appearance and sound seemingly obvious for the function and aesthetic of the design. Touching and bodily sensation can be seen as necessary for interacting with the speaker design, and feeling is important as the module focuses on emotion in design.

Feeling has more variation in the results than other modalities. The PCCs for feeling are more variable and weaker, with feeling versus sound having an almost negligible correlation. The correlations with other modalities are slightly stronger (both positive and negative) but none can be said to be “strong” correlations, the strongest being for appearance (positive) and touching (negative). This suggests that there is less clear correlation between feeling and other imagery modality responses and so feeling cannot be used to predict how participants will score on other imagery modalities. While these results are interesting, it would be beneficial to explore further by repeating the investigation with a larger group of participants.

PCCs between the PSIQ and module results were calculated using the mean scores per modality for each participant. Out of the 64 PCCs calculated for PSIQ means versus module results, 54 (85%) had a negative correlation, with 15 (23%) being strong negative correlations. The overall mean versus the overall grade correlation is -0.4288 (negative correlation), suggesting that the higher a participant’s imagery score is, the worse they perform in the module. There were no outlying results for the smell, touching or bodily sensation modalities versus the overall module grade. Appearance and taste however both have strong negative correlations when compared with the overall grade. Appearance versus overall grade gave the PCC -0.5343 and taste -0.5861, both of which suggest that these modalities have a particularly negative correlation with how a student performs in the DM300 module.

The sound modality provided several interesting outliers when compared with other results. The PCC for the sound modality means versus overall module grade, the exhibition grade, and the journal grade were all almost negligible while most other modality mean PCCs had stronger negative correlations. While the sound versus the exhibition breakdowns did feature two positive correlations, these were still weak, showing almost no correlation between the data. The variation of the sound modality was emphasised when considered by question, with clear variations seen in the PCCs. These ranged from negatives, such as Q4 versus the quality exhibition grade at -0.5125, to positives such as Q3 versus the experience exhibition grade (0.3726). However, the overwhelming result for the sound modality was that there were weak correlations between how participants responded and their grade attainment in DM300, suggesting that there is no true correlation between the two. This is surprising given that the module project is to design a speaker, but since the task ends at detailed design and does not feature working prototypes, it could be that students do not need to utilise their sound imagery

to the fullest. The lack of correlation could be confirmed with further studies on a larger group of students.

While there are similarities between most modalities, the feeling modality is striking as having more variable and more positive correlations with the module grades, but a higher number of negative correlations with other modalities. The PCC for feeling versus overall grade is 0.2605 which is the only positive correlation with the overall grade. Given that the module has a heavy emotion theme, this is an interesting result.

4.5 Conclusion

The aim of the design, emotion and mental imagery investigation was met and the assumption that engineering design students will perform better in a design module with an emotion theme if they report experiencing more vivid mental imagery was shown to be incorrect. While failure was avoided as a correlation was shown, a negative correlation between mental imagery reports and DM300 module grades was found. This is a fascinating result as it potentially disproves any theory that a designer's vivid mental imagery automatically improves design outcomes. However, the participant pool for the study being only ten leads the researcher to suggest repeating the investigation with a larger participant pool to confirm the results. Further to this, the PSIQ results were high across the board, with no possible aphantasia reported and minimal low responses. Again, this is further evidence that the research should be repeated with a larger participant pool. Additionally, it would be beneficial to further investigate the apparent lack of sound correlation with module grades in a project designing a device for sound.

In terms of the success of the PSIQ, visual imagery is often better understood as it is more commonly discussed in research and media which could be a reason for the varying responses throughout the multisensory questionnaire. This indicates that a single questionnaire measuring mental imagery vividness to determine the complex experience of mental imagery is not suitable in design contexts. Of note are the findings that the question responses are subjective to each person, which is further supported by similar results in Chapter 3. These findings highlight additional variables impact the outcomes and make it difficult to judge fully whether the PSIQ is a successful measure of mental imagery for novice engineering designers. Finally, it was found that the questionnaire may not be suitable for engineering design and

leads the researcher to question if a new questionnaire that focuses on engineering design would be less subjective and a better solution for the research.

There were many positive gains from the investigation including that students are a favourable focus group for the research, that researching the emotion modality is a difficult element to investigate since it is a highly subjective experience, and that assumptions are hard to make with mental imagery research. The negative correlation found between mental imagery vividness and the module grades was surprising yet interesting and confirms that the research should be repeated with a larger participant pool to confirm or reject these findings.

Part B: Research development

Chapter 5: Research approach

5.1 Adopted research approach

Research approaches are procedures that cover the entire research process, from initial assumptions and research questions, through to analysis and conclusions. They help to create the plan or proposal for the work (Creswell and Creswell 2023), enabling the researcher to answer their problems in a justified manner. There are a range of design research approaches and methodologies to assist in explaining and inferring meaning of the design world. A research project will typically review these, adopt a research approach and methodology, before finalising a project-specific research design and roadmap. While it is common for the approach to a research project to be decided early in the project timeline, it is acknowledged that this does differ depending on the project in question. Due to the subjective and vast nature of mental imagery research, the lack of knowledge the researcher began the project with, and the gap in the literature meaning that there is a significant deficit in the existing material available, knowledge expansion work consisting of interviews with designers and an initial study on design students was undertaken to begin the project. Early in the literature review, it was found that mental imagery research in engineering design is scarce, and so further knowledge building was required to confirm the research focus, and the knowledge gap that existed, without overwhelming the project with data.

Often researchers will bring with them their own moral and ethical compass (Creswell and Creswell 2023), unintentionally or not informing the basis of their approach to a project, even if philosophical ideas are concealed within the research. The “assumptions” are often referred to as a personal worldview, “paradigms” of research, or “epistemologies and ontologies” (Creswell and Creswell 2023), with ontology depicting a researcher’s assumption about human existence, and epistemology a perspective on building knowledge (Hesse-Biber 2010).

There are many examples of research approaches or methodologies, with the most prominent for discussion being postpositivist, constructivist, transformative, and pragmatic. Postpositivism, often referred to as a “scientific method” is a traditional form of research that holds more for quantitative research and follows-on from positivism (Creswell and Creswell 2023). Constructivism, on the other hand, often referred to as a “social constructivist”

approach, encourages researchers to attempt to understand the world around them through subjective human experiences, and it usually involves qualitative research and more open-ended questioning (Creswell and Creswell 2023). Conversely, a transformative approach views that constructivism is not enough for helping marginalised people, and that research should be political.

For pragmatic approaches, the research arises out of incidents and actions, putting focus on the research problem itself, rather than a specific method or approach. Typically, a mixed methods approach is used which allows the researcher to avoid committing to one research worldview: the onus is put on truth of the data itself, with this defining what and how to research the problem (Creswell and Creswell 2023). Creswell and Creswell (2023) stated that pragmatists believe in both an external and internal world within and out-with one's mind, suggesting that all elements of the human experience are equally as important in research. Following the initial work to understand the problem area, it was decided that a pragmatic philosophy was appropriate for the project. Pragmatic research allows for more freedom, with no specific method or approach selected at the start and instead encourages method development based on the research area. As mental imagery is a subjective experience, the ability to quantify it would be beneficial to avoid relying solely on personal response. Further, the belief that there is both an internal world within one's mind, and an external world that is equally important to research resonates with this project: mental imagery is an inherently subjective experience that occurs within a person's mind, while engineering design relies heavily on external output that interacts with the world. For researching mental imagery within engineering design, a pragmatic approach that puts emphasis on the overlap of internal and external feels appropriate for the challenge.

The research design of a project, also referred to as "procedures" or "strategies" of inquiry, are the method(s) in which the research is conducted within a set methodology, and are the types of inquiry that allow for direction in a project (Creswell and Creswell 2023). Qualitative design approaches involve design methods that focus on narration of a story and words, rather than a numerical interpretation, and are often grounded in the views of participants. There is an emphasis in qualitative studies on the descriptiveness of the outcomes, and a researcher's interpretation of these descriptions, where a participant is encouraged to share and discuss their own experiences (Creswell and Creswell 2023). Qualitative studies are

often an attempt to discover new ways of understanding the subjective human experience (Hesse-Biber 2010).

Alternatively, quantitative research designs use more objective approaches where in the relationship between variables is compared and tested via numerical approaches, and often with statistical analysis and methods (Creswell and Creswell 2023). Quantitative research can include single-subject type experiments wherein variables are minimised to look at specific problem areas, researching independent variable differences or causations, or considering correlations between variables or problem areas to find trends, specific impacts and attitudes (Creswell and Creswell 2023). The positives of a quantitative research design include the ability to protect against bias and control of the findings, within reason (Creswell and Creswell 2023), through the reduction of the human experience to a numbers-based system.

A mixed methods approach to research design is the combination or integration of both qualitative and quantitative research strategies that consider the need to understand the entire research problem, rather than stipulating specific approaches or methods (Hesse-Biber 2010; Creswell and Creswell 2023; Kumar 2019). A narrative approach is used to add meaning to numbers, or vice-versa (Hesse-Biber 2010), for example by using numerical strategies to quantify inherently subjective experiences, as is often the case in protocol analysis studies. Mixed methods research combines or integrates the data from both qualitative and quantitative approaches to gain insights (Creswell and Creswell 2023). It aims to reduce weakness in research by considering that all methods and approaches hold some inherent bias, and so avoiding one single approach theoretically helps improve validity (Creswell and Creswell 2023; Kumar 2019). The advantages of a mixed methods approach include that it can enhance the research, is better for complex situations, can enrich the data, and increases the evidence to support a research outcome (Kumar 2019). Conversely, the disadvantages can include the need for more work and resources, as well as the requirement for additional skills and higher levels of participant populations, and the potential for disagreements in the research (Kumar 2019).

Mixed method research designs can be convergent, explanatory sequential, exploratory sequential, or complex, with embedded core elements (Creswell and Creswell 2023). Convergent mixed method approaches are a core form of mixed methods research which merges both sides of data to provide a more in-depth analysis of a problem, with data collected in conjunction, and interpreted as part of an overall. Explanatory sequential begins

with quantitative research and analysis, which is then followed by qualitative research to provide more detail to the initial findings, while exploratory sequential follows the pattern in reverse (Hesse-Biber 2010; Creswell and Creswell 2023). For complex mixed methods approaches, one or more of the core designs is factored into a process, such as by conducting a qualitative experiment, then using this to explain quantitative findings as a result (Creswell and Creswell 2023). A mixed methods research methodology will be followed for this research, with a specific focus on a complex mixed methods research design. Both qualitative and quantitative methods will be used to gather narratives on the subjective experiences of mental imagery from participants, while using quantitative methods to quantify the experiences in a supportive format. The complexity of the mixed methods design comes from the use of different methods to collaborate findings throughout the project. Given the subjective nature of mental imagery research, often described as akin to reading a person's mind, there is an inherent reliance necessary on qualitative findings. This is supported by the findings in Chapter 3's interviews, wherein an individual's explanation of their mental imagery experience was often more comprehensive than the mental imagery vividness measurement questionnaires. However, with design cognition research, a well-proven method for understanding cognition which can be applied to mental imagery research, is protocol analysis, a method that attempts to quantify the subjective research of design cognition. The combination of qualitative findings and quantitative research methods signifies the suitability of a mixed-methods approach.

5.2 Research design

5.2.1 Research focus

One clear gap missing from the literature is research on mental imagery during the design process itself, and particularly in engineering design. While studies have been conducted into mental imagery and its interactions with specific elements of design, such as sketching (Kavakli and Gero 2001; Tedjosaputro *et al.* 2014; 2017; 2018), or the use of imagery during idea generation (Dahl, Chattopadhyay and Gorn 1999; 2001), or even the vividness of imagery during design ideation (Hart and Hay 2022), significantly less has been undertaken on the occurrence and experience of mental imagery during the entire engineering design process. There is an assumption that imagery occurs at the start of the process, or to visualise the customer's use of a product (Dahl, Chattopadhyay and Gorn 2001), yet designers

also claim to either not utilise imagery at all (Dahl, Chattopadhyay and Gorn 1999), or that it is almost second nature to them, as discussed in Chapter 3. Additionally, there are many varying definitions of mental imagery that appear to be dependent on the research field in question, and as seen in Chapters 3 and 4, there are also clear variations in the experience of mental imagery. This all leads to asking when and how do designers experience mental imagery during the engineering design process exactly, how can this be measured, and how do we define the experience? By placing empirical focus on the design process as a whole, rather than the early stages alone, an understanding into how the experience of mental imagery varies throughout the design stages can be gained, furthering previous investigations of mental imagery in early design stages (Dahl, Chattopadhyay and Gorn 2001) and allowing for a comprehensive view of the experience of mental imagery in engineering design.

The field of engineering design has been selected largely due to the researcher's area of expertise and background. However, the field of engineering design as a research focus provides benefits for this topic due to the detail, steps and methodologies included in the product and engineering design process. The design process, especially that which is taught to university-level students on engineering design courses, begins at the start of a design task, with the introduction of a design brief and brainstorming, and leads designers through to the point of manufacturing a product. This ensures the consideration of all elements of designing a new solution and means that designers are designing in different ways at different steps. For example, the tools, methods and cognition used during idea generation will not be the same as that used during evaluation points. Most commonly, designers and design students will work to a design methodology, such as the Double Diamond (Design Council 2025) or Pugh's Total Design (Pugh 1991) to ensure they are meeting all of the necessary steps to create an appropriate solution. Further to this, there is often encouragement to create a useful and novel solution, suggesting that memory and imagination imagery may have an impact on the mental imagery experience during the design process, and if this is the case, it is reasonable to hypothesise that other imagery elements may also have an impact.

The literature found in Chapter 2 suggests that design cognition is different in student versus experienced designers (Gero and Milovanovic 2020; Shealy *et al.* 2023). The interviews in Chapter 3 appear to support this with respect to mental imagery, with expert designers claiming not to use it much, also supported by Dahl, Chattopadhyay and Gorn's research (1999). Assuming this to be true and considering that little to no research has been undertaken

previously on the mental imagery experiences in engineering design, it is arguably logical to conduct the research with respect to students in the first instance. Engineering design students are at the start of their career and therefore will have fewer external impacts on their design cognition, such as a wealth of experience in design projects that will inevitably impact on their cognitive process. For example, through the utilisation of previous designs from memory or advanced skills with design software that could impact their process and decisions. Additionally, while experienced designers can be assumed to have their design process, there is potential for impact in novice designers to adapt their design practice, and the support they receive throughout their education. It therefore is reasonable to conclude that answering the research questions below with respect to student designers is a logical place to begin for such a large knowledge gap. Additionally, one reason for experts claiming to not “use” mental imagery could be due to a lack of understanding about what they are experiencing. With students being the next generation of expert engineering designers, it would be beneficial to build their understanding of the experience during their own design process before they move into an industry career.

A further focus of the research will be on diversity and inclusivity in engineering design education. Design cognition is a subjective experience, and everyone’s way of designing will differ, depending on many potential elements, such as skill, education, and accessibility. Heylighen and Gero (2011) researched the nature of design ability through a focus on an architect who has continued designing and teaching despite having lost their sight. It was found that the way in which the individual generated ideas was unchanged, despite this loss of the visual sense, and yet other elements of their design process had changed to accommodate. One example is that they relied more heavily on non-visual sensory qualities, both in design and communication of design. Through the understanding this research provides, it is possible to query if researchers and design educators are overlooking an element of inclusivity through mental imagery experiences. The literature revealed that individual experience of imagery is diverse, from the level of vividness to the processes that are utilised, and so the impact of this on design cognition could be a contributing factor in design inclusivity improvements. If it is known that individuals experience mental imagery differently, why is there commonly an insistence on teaching students in the same manner, with little to no consideration for cognitive diversity? Furthermore, can this understanding be used to improve inclusivity in design, teaching and assessment?

Compiling the different areas of focus for the research of mental imagery experiences during the design process of engineering design students, with a view to improving inclusivity in engineering design education, leads to the following research questions:

- RQ1. How do engineering design students experience mental imagery during the design process, and can we map these diverse experiences?
- RQ2. By understanding the individual experiences, how can we define mental imagery in engineering design?
- RQ3. In what way can this understanding and definition be utilised to improve inclusivity in engineering design education for students?

The research questions will be the focus of the investigations throughout the remainder of the thesis. A complex mixed methods approach is appropriate for answering the research questions posed through a mix of qualitative and quantitative methods. The subjective nature of the mental imagery experience means that the research will be largely qualitative in nature, as even the quantitative methods of measurement, such as protocol analysis, still rely on reporting personal experiences. Despite this, quantitative methods and statistical analysis enable a way to quantify this inherently subjective experience and support the mapping and defining of diverse experiences. The methodology followed will be a QUALquan approach (Hesse-Biber 2010) due to the heightened level of subjective, qualitative approaches involved in mental imagery research.

5.2.2 Research design

As displayed in the research map (Figure 5.1), there are various elements and methods that will be employed to answer the research questions. These will consist of a mixture of qualitative (marked blue in Figure 5.1), quantitative (green) and mixed methods (purple), and each element will be based on either theory generation (pink) or the findings from a previous method (orange). The literature review (qualitative method) resulted in findings that have led to the need to create a framework, and to the research focus for the project. Further, it also led to the assumptions that formed the basis of the preliminary design, emotion and mental imagery study detailed in Chapter 4 (quantitative method). These findings contributed to the development of the research focus with the outcome that assumptions about the links between mental imagery and engineering design education may be incorrect. However, it is noted,

again, that the small sample size requires further investigation before final conclusions can be made. In addition to this, the findings of the interview study (Chapter 3) have contributed to the research focus through a greater understanding of how designers explain their mental imagery, and confirmation that there are a wide range of diverse experiences of mental imagery, even amongst creative professionals.

Following the creation of a framework for researching mental imagery, two studies were undertaken to answer different elements of the research questions. The first was in addition to the preliminary study in Chapter 4, and to confirm if engineering design students will perform better in a design module if they have more vivid mental imagery. By further establishing a proof or disproof of this assumption, the work will contribute to the understanding of how mental imagery is experienced in engineering design education. The study will use a psychometric questionnaire to measure multisensory imagery (Andrade *et al.* 2014) of student designers, helping to define what elements of the mental imagery experience impact on their design cognition. The study will be quantitative in nature due to the use of a quantitative questionnaire, but it should be noted that these are still subjective response questionnaires, and so there remains a qualitative element. Further, statistical analysis will be used to analyse the findings of the data and any correlations between mental imagery experiences and design module outcomes.

One clear finding from the literature review, is the benefit of conducting a protocol analysis study to research design cognition (Gero and McNeill 1998; Suwa, Purcell and Gero 1998; Hay *et al.* 2017). While the details were finalised following the study on mental imagery in design education, a protocol analysis study was to be undertaken to map and gain insight on the diverse experiences of engineering design students during the design process. It is acknowledged that while a study on multisensory imagery would be ideal, for the purpose of this research, the focus will be solely on visual imagery. This is in part due to time constraints, and in part due to the abundance of literature on visual imagery in design confirming that it does play a role in design (Kokotovich and Purcell 2000; Maciel *et al.* 2021) and ensuring that there would be an outcome for visual mental imagery's role in the design process. The aim of the study was to define the experience of mental imagery in engineering design. This study took a mixed methods approach as protocol analysis aims to quantify a subjective experience, meaning quantitative analysis of qualitative research. The data was analysed quantitatively by analysis of code and link occurrences, and qualitatively by mapping the participant's imagery

in the design process. The experience maps are intended to create a visual interpretation of the results and depict a clear path of mental imagery experience during the individual design process.

The goal of the research is to have three outcomes from the studies, combining all findings from the project into three final research question solutions: the mapping of diverse mental imagery experiences of engineering design students, a findings-based outcome that supports a definition of mental imagery in engineering design, and a theory-based outcome that leads to a solution for using the research to improve inclusivity in engineering design education. The findings of both studies should contribute to the development of both final outcomes. Further, while Figure 5.1 depicts the forward flow of research throughout the project, the findings allow the reconsideration of the literature uncovered during the review in Chapter 2, ensuring a proven contribution to the research field.

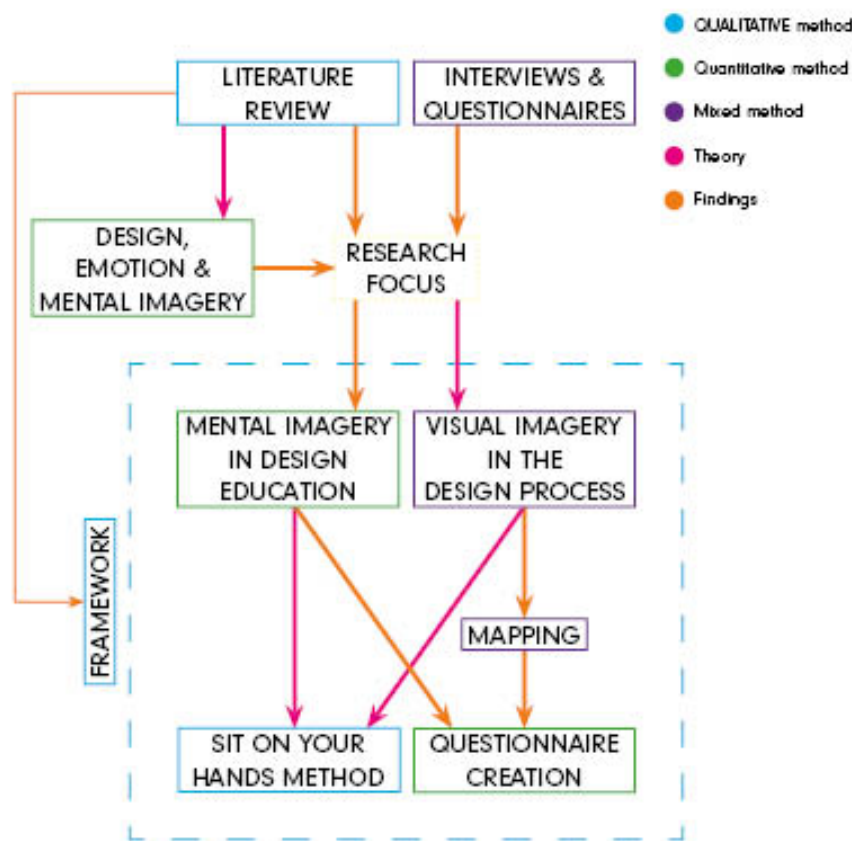


Figure 5.1: Research design map

5.2.3 Dissemination and research outputs

The dissemination of the research findings of a project is an important consideration to ensure robust validity, both via the peer review process of all reliable sources, and through the need to share and communicate the work within a global community of researchers and academics. Sharing the work allows for the findings to be added to the conversations within the research field, and for any necessary critiques of the work. The research in this project will be disseminated in a variety of manners:

- Journal articles (a paper published in a peer-review academic journal) detailing the findings of Chapters 8 and 9, and the evaluation and verification of the SoYH method are pending.
- Conference paper (published as part of the proceedings of a conference) and conference poster presentations: the literature review (Chapter 2) was published alongside the development of a framework for researching mental imagery (Chapter 6), as found in Appendix 7. This work was published as part of the International Conference on Engineering Design in 2023 and is titled “A framework for understanding mental imagery in design cognition research”. An initial version of this work was shared at the Tenth International Conference on Design Computing and Cognition in 2022 as a poster presentation, found in Appendix 8. The work detailed in Chapters 4 and 7 detailing a study investigating correlations between mental imagery vividness and educational attainment are to be published as part of the planned 28th International Conference on Engineering and Product Design Education (accepted and pending publication in September 2026). The paper is titled “Mental Imagery Vividness and its Impact on Learning Attainment in Design Education”.
- Thesis: the current document compiles the entire body of work for the project as a summary of the research undertaken.
- Conference workshop: In addition to the written research outputs detailed, a workshop was developed and delivered at the 27th International Conference on Engineering and Product Design Education in 2025 that summarised work from Chapters 1 through 8 and provided evaluation of the Sit on Your Hands method, detailed in Chapter 10. A proposal for a follow-up workshop to

further validate the Sit on Your Hands method has been submitted for review for the 28th International Conference on Engineering and Product Design Education in September 2026.

5.3 Summary

This chapter outlines the research approach and design for the current project, as well as detailing the dissemination of the research and future plans. It follows on from the knowledge expansion section in Part A, which summarises the initial findings for the research that have been used to form the knowledge gap. The chapter provides detailed understanding of design research terminology and elements, such as the differences between various research approaches and philosophies. The final adopted research approach is outlined as a complex mixed methods approach. The research focus is to define and map mental imagery in the engineering design process, specifically for student engineering designers, and to improve inclusivity in engineering design education. This will be completed by answering the three research questions detailed in Chapter 5.3.1. The research design map, found in Figure 5.1, detailed the proposed work overall and the interconnections of each element of the research. The next step in the project was the development of a framework for researching mental imagery to help define the experience in engineering design.

Chapter 6: Development of a framework for researching mental imagery

6.1 Framework development

The field of mental imagery research spans disciplines from uses for mental imagery in the field of psychology (Holmes and Mathews, 2010) to benefits of imagery utilisation in the design industry (Dahl *et al.* 2001; Goldschmidt 2007). Each person can have an entirely different experience of imagery, given that it exists solely within one's own mind (Maciel *et al.* 2021). This brings challenges due to the scope of the research: it must be inclusive enough to produce context and justification but be achievable within the project restrictions. When conducting the literature review in Chapter 2, a list of subtopics was generated to map the research. This list of subtopics ranged from neurobiology to memory imagery, and was organised within a spreadsheet, with each paper being recorded against any relevant subtopics. While the focus of the literature review was on mental imagery in design, the search area was expanded to include non-design and scientific fields in order to gain a wide-ranging insight into the current state-of-the-art mental imagery research. The full list of subtopics gathered from literature sources can be found in Table 2.1 and was used as the first step towards developing a framework. Following the initial draft of the literature review, it was found that the 50 subtopics could be gathered into groups of similar overarching themes. The initial grouping of topics was neurobiology and psychology, dimensional ability (vividness, measures, and abilities), processes (cognitive ability, and style and behaviour), and modalities (multi-sensory imagery). This grouping can be found as an initial framework for understanding mental imagery research (Version 1) in Figure 6.1, with Figure 6.2 depicting the categorisation of subtopics by grouping.

An initial framework (Appendix 8) was first displayed at the Tenth International Conference on Design Computing and Cognition in 2022. It depicts mental imagery research split into two separate research areas: neurobiology and psychology, being the physiological explanation for mental imagery, and the elements of the mental imagery experience, being how an individual experiences mental imagery. These elements were then grouped by the research studying them in an engineering design setting, outlined with a blue box in Figures 6.1 and 6.2.

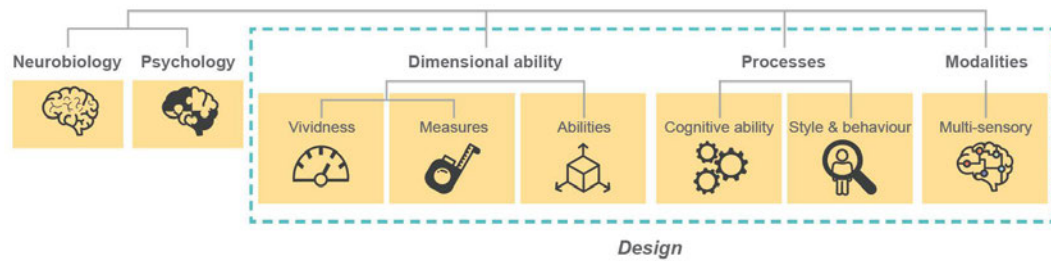


Figure 6.1: Framework for understanding mental imagery research, version 1

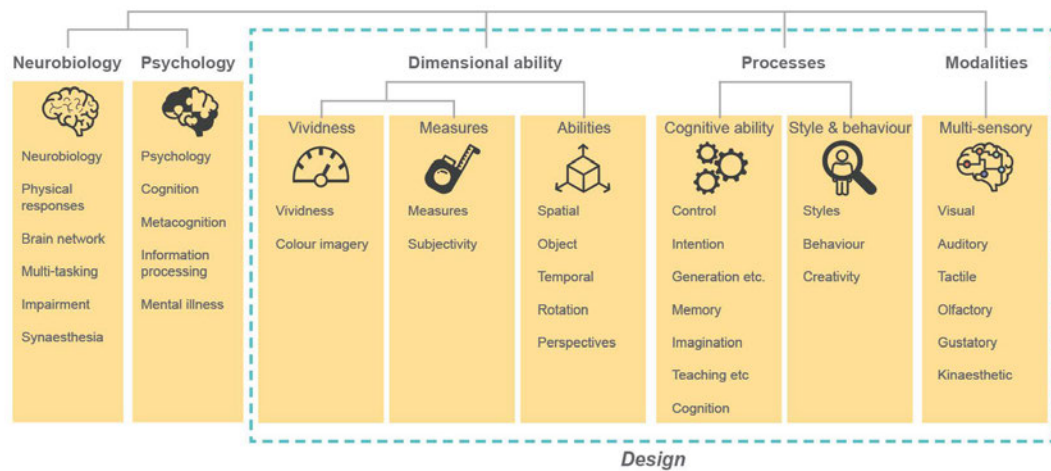


Figure 6.2: Version 1, subtopic categorisation (as per Appendix 8)

While Version 1 marked an appropriate starting point for developing a research framework, there remained an element of complexity to the structure. Further research and literature analysis was undertaken, and the subtopics were regrouped in a more streamlined format. The restructured grouping, which can be found in Figure 6.3 (Version 2), split the research into that which acts as an overview of the inner workings of mental imagery, and three key conceptual viewpoints of mental imagery: dimensions of imagery ability, imagery processes, and imagery modalities. This restructured grouping allows for a simpler framework that is easier to understand, and a more logical categorisation of the subtopics found in mental imagery research. This framework has been developed with the expectation that it can be employed to research mental imagery within different fields, for example, within engineering design.

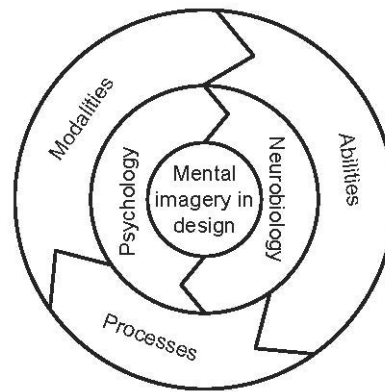


Figure 6.3: Framework Version 2

With the key conceptual viewpoints of mental imagery determined, a method of communicating this framework needed to be created that allowed for ease of sharing and understanding. The graphics seen in Figure 6.4 are the initial iterations of this method of communication (Version 3). Following a development period, the framework for understanding mental imagery research (FMIR) (Macfie, Hay and Rodgers 2023) was created, as can be seen in Figure 6.5. The framework was verified through its application to engineering design, as discussed in Chapter 6.1.2. Figure 6.5 provides a graphical interpretation of the framework and depicts three key conceptual viewpoints that formulate research into the mental imagery experience, with all viewpoints interconnecting, and then converging back into the centre. This depicts the argument made in Chapter 2 that mental imagery is not a one-dimensional experience and consists of varying elements and viewpoints that should be considered routinely throughout research. These three conceptual viewpoints are as follows: dimensions of imagery ability (Dv), imagery processes (Pv), and imagery modalities (Mv). Dimensions of imagery ability are topics such as vividness, spatial ability, and measurements of imagery; imagery processes include tasks such as image generation and retention, or the use of memory images; and imagery modalities consists of the different senses in imagery, as well as the connection and impact of emotion. The full list of subtopics mapped out with respect to the viewpoints can be found in Figure 6.3, though it should be noted that the inclusions are not limited to this list and are mapped as discovered so far in the research. Whilst these viewpoints can be standalone topics, it is important to keep in mind how closely they all interact with each other. For example, dimensions closely interact with modalities in that individuals can have differing levels of vividness across modalities (Maciel *et al.* 2021), and memory imagery (process) can impact on emotion and modalities (Taruffi and Küssner 2019).

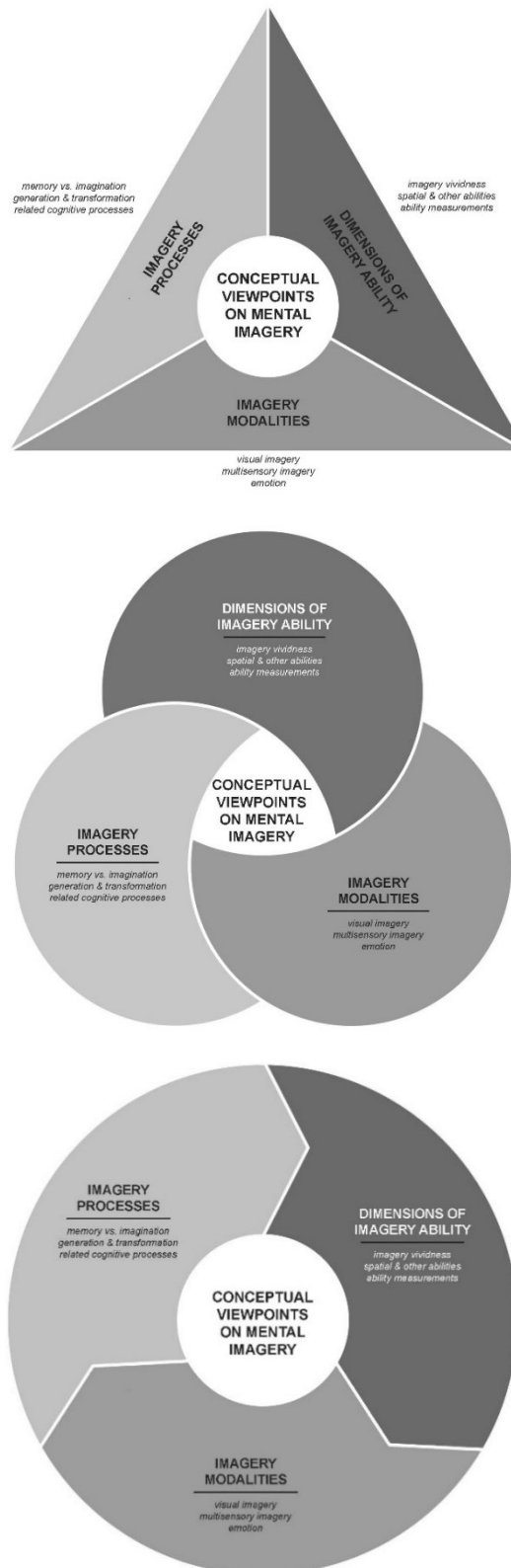


Figure 6.4: Framework Version 3, initial iterations

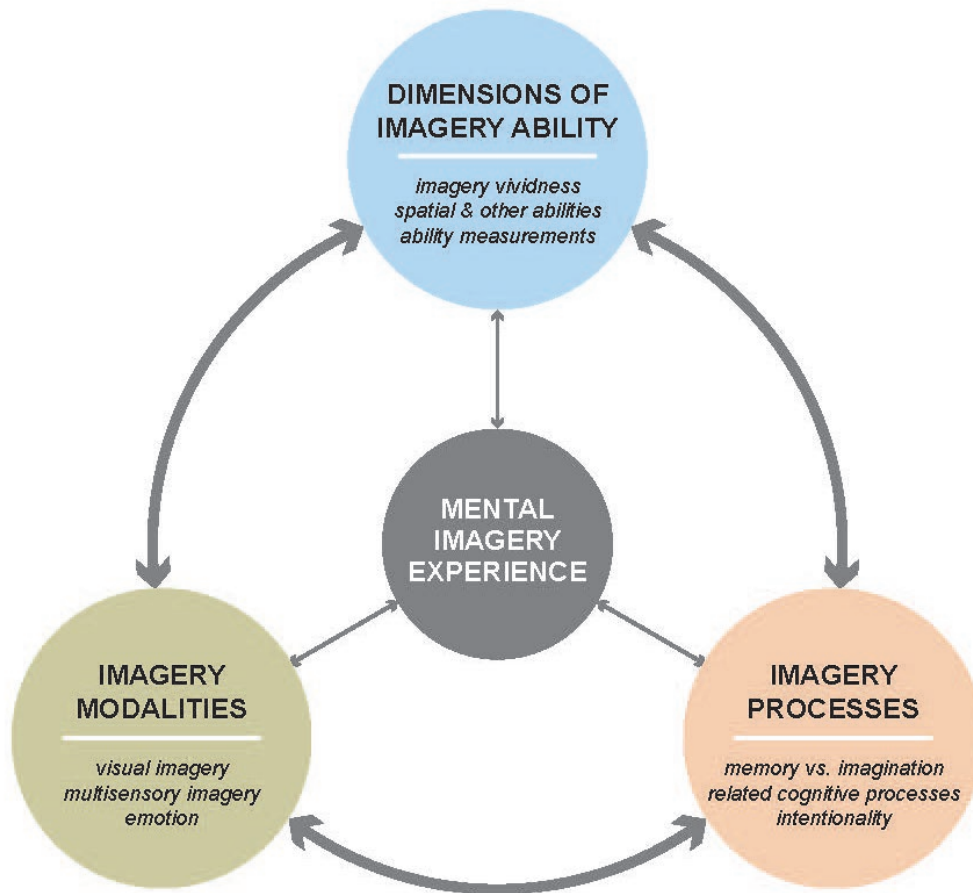


Figure 6.5: Framework for researching mental imagery (FMIR)

6.2 Framework verification

The literature review conducted for this project provided insight into how mental imagery can be successfully researched within the context of engineering design. It allowed the development of a framework categorising the elements involved in mental imagery research. Whilst the research is limited by the amount of literature on the topic in engineering design, it was found that research in other domains, such as architecture, could have relevance to the field by applying the FMIR in the context of engineering design. Returning to the literature in Chapter 2, the compiled papers can be organised by the FMIR viewpoints that they cover. Figure 6.6 shows a graphical representation of the viewpoints allocated per paper reviewed in Chapter 2, with each paper represented by a single star. Appendix 9 contains the full list of papers alongside a notation of the allocated viewpoints. As Figure 6.6 depicts, there

is a consistent representation of the viewpoints and their interconnections across the range of literature reviewed. 38% of the papers reviewed represented one viewpoint in the framework, while 46% represented two, and 16.00% represented all three viewpoints. The highest occurring viewpoint in the literature review was Dv, with 68% of papers covering the topic, while Mv and Pv occurred 53% and 57% respectively. Dv made up 18.50% of the papers that covered just one viewpoint, Mv 8.50% and Pv 11%, while the split of papers covering two viewpoints was relatively even: Dv and Mv was 16%, Dv and Pv 17.50%, and Mv and Pv 12.50%. The reasonably even distribution of papers covering the viewpoints and their interconnections confirms that the consideration of different elements of mental imagery are important to the research.



Figure 6.6: Literature categorisation (Chapter 2) according to framework viewpoint

The literature categorisation can be examined with respect to the findings detailed in Chapter 2, and how they interact within the FMIR. Gallagher (2019)'s discussion of creators with aphantasia, or low imagery vividness, falls squarely in the Dv viewpoint given its focus on the dimension of mental imagery vividness, and suggests it is feasible that different designers use different sensory perception at different levels. Bainbridge *et al.* (2021) is also categorised by its research on imagery vividness and its use of the think-aloud method for measuring design experiences. Additionally, various other papers discussing protocol studies

that employ the think-aloud method for measuring design data, such as Gero and McNeill (1998), Adharamadinka and Junaidy (2022), and Cindioglu, Gursel and Surer (2022), are also encompassed by Dv and provide a method for the measurement of mental imagery experiences in engineering design.

There are many processes (Pv) thought to be involved in mental imagery, with papers such as Pearson (2007) and Kosslyn, Behrmann and Jeannerod (1995) discussing various behaviours that have been found to make up individual imagery experiences. Pearson (2007) discusses differences between memory and fantasy imagery, and Kosslyn, Behrmann and Jeannerod (1995) the actions that can be involved in imagery generation, from forming to transforming of images, all of which may have a connection with how designers design. Often queried is mental imagery in design cognition and what exactly this entails. Christensen and Schunn (2009) covered this topic through their discussion of the feasibility to design through mental simulation alone.

Given how often it is believed that visual imagery is the prevalent form of imagery experienced, research on multisensory imagery is an important inclusion in the review, such as Bensafi *et al.*'s (2012) research on fMRI evidence of similar brain responses between imagery events and actual perception. A significant feature of the Mv viewpoint is the inclusion of emotion alongside multisensory imagery. The vast range of research on emotion and mental imagery highlights its importance alongside other imagery modalities with its high impact on the mental imagery experience, as is discussed in more depth in Chapter 2. Holmes and Mathews (2010) provide evidence that higher empathy can result in more intense imagery events, an important consideration for designers considering the research by Dahl, Chattopadhyay and Gorn (2001), also discussed in Chapter 2.

An important detail of the framework that should be considered during mental imagery research is that each and all of the viewpoints interact with each other. It is difficult to consider one element of mental imagery without keeping the others in mind, particularly when exploring how it is experienced within engineering design. In terms of Dv and Pv viewpoints, Heuer, Fischman and Reisberg's (1986) paper researching colour imagery and colour memory could have clear connotations for engineering design research given the importance of colour use in design. Athavankar (1997) presented evidence that mental imagery utilisation in design could reduce the number of actions a designer needs to make in their design work, which connects to both Dv through the relevance of imagery vividness, and Pv by its discussion of

cognitive actions. Additionally, Dahl, Chattopadhyay and Gorn (1999; 2001) found that intentionally utilising mental imagery within the design process by way of visualising the end user of a product (Pv) provides a designer with a greater sense of empathy (Mv), leading to more useful final products.

The interconnection of Dv and Mv viewpoints is arguably the easiest to discuss with multisensory imagery and vividness of imagery being regularly affiliated. An example of this is that Maciel *et al.* (2021) found that individuals can experience differing levels of mental imagery vividness for different modalities. The relevance of this to engineering design is clear through its potential for experience differences between designers. Further, there is the issue of the subjectivity of the mental imagery experience, as Milton *et al.* (2021) discusses, and whether individual descriptions of imagery are true to a shared understanding. In design, the implication this could have, particularly on teamwork, cannot be understated as it could impact on communication and sharing of ideas. Furthermore, Andrade *et al.* 2014, presents the PSIQ, a psychometric questionnaire that allows the measurement of the vividness of different mental imagery modalities, a measurement form that could be used in design cognition research to gain insight of multisensory imagery experiences in design.

Dahl, Chattopadhyay and Gorn (2001) provide a clear connection between the Mv and Pv viewpoints through their research on visual imagery and empathy during the design process. Considering that there is an intricate connection between emotion or empathy and imagery (Taruffi and Küssner 2019), it is feasible that there is a link between intentionality, or other processes, of mental imagery (Pv) and emotion in design (Mv). The connection between emotion and design has been discussed previously in this chapter and Taruffi and Küssner (2019) provide additional points of discussion for its connection through different processes of imagery. Further, Pearson, Rademaker and Tong (2011) undertook a mental imagery generation experiment in a darkened room, detailing a connection between the visual modality (Mv) and the generation process (Pv), research which could help to understand how engineering designers generate imagery during the design process, and the impact of environment.

Finally, as displayed in Figure 6.6, there were multiple papers included in the literature review that connected all three viewpoints together. Goldschmidt (2007) discussed visual imagery as being a starting point in the design process and the importance of the connection between mental imagery and sketching. This covers all viewpoints through its focus on the

individual experience of visual imagery during the design process. The 1999 paper from Dahl, Chattopadhyay and Gorn provides evidence of the importance of visualising the customer use through visual imagery to create more useful products, establishing the idea of visual imagery as a process through its importance to empathy. Finally, Kavakli and Gero (2001) present research showing that mental imagery is subjective and personal to the individual, with every person have their own unique experience of imagery across the modalities, dimensions and processes. This could in turn impact on their own experiences of imagery within the engineering design process.

6.3 Summary

The framework for researching mental imagery in design cognition (FMIR) has been verified through its application to the field of engineering design, as detailed in Chapter 6.2. To summarise the chapter, there were found to be three key conceptual viewpoints for researching mental imagery: mental imagery modalities, dimensions of imagery ability, and mental imagery processes. These viewpoints were found to be interconnected and are largely discussed within relation to at least one other viewpoint in many of the research papers reviewed. It should be noted, however, that despite the wide-ranging list of subtopics gathered in Figure 6.2, the fields of mental imagery and design cognition research are ever developing, meaning that further additions and alterations to the framework could be made.

The FMIR is the first step in developing a definition for mental imagery, particularly with respect to the experience in engineering design, and the framework supports future work in creating this definition. This is despite there being an absence of research into the experience of mental imagery within engineering design, as cross-disciplinary research can be utilised through the framework to better understand the diverse cognitive experience as a process, which allows for the application to engineering design. As for the details of the framework in this project, the literature review in Chapter 2 and the FMIR findings support one another, with the viewpoints found confirming that the literature is appropriate for the project, and the literature review findings supporting the relevance of the viewpoints. This connection provides a better structure to the research, particularly within this thesis through its improved organisation of the literature.

The framework was further used to structure the remainder of this research thesis by ensuring that all research studies and outputs relate to the framework viewpoints. This ensured that the work is relevant to mental imagery research and allowed for further evaluation of the FMIR. The mental imagery and design education study covered the topics of imagery modalities, dimensions of imagery ability and their overlap through its focus on vividness of multisensory imagery in student engineering designers. The visual imagery in the design process study focused only on visual imagery, removing the element of multisensory imagery, but covered the remainder of the experience of mental imagery in the design process, accounting for both dimensions of imagery ability and imagery processes. The goal of this study was to map the experience of visual mental imagery on the design process through the development of a protocol analysis study using the FMIR as a basis for the coding scheme.

Part C: Investigations and reflections

Chapter 7: Mental imagery and design education

7.1 Introduction

The preliminary study detailed in Chapter 4 demonstrated that a full investigation is required. In addition, there is a clear benefit to studying mental imagery in an engineering design education context, in part due to the lack of external influence on a student's design process, and to shape an engineering designer's professional practice. There are also benefits to recognising and supporting a wide range of student developmental needs within learning environments. The PCCs, Table 4.5, calculated to compare the PSIQ results with module grades returned largely negative correlations. These results are considered and built upon in the study detailed within this chapter. Additionally, it may enhance insights by conducting the study with another module for the purpose of comparing the results and analysing any negative correlations.

Chapter 4 investigated the assumption that engineering design students will perform better in a design module with an emotion theme if they report having more vivid mental imagery through analysis of student outcomes in one design module. The current study measured the results of two different modules, without a specific focus on the impact of emotion, but the measurement of mental imagery vividness versus final module grade remained the same. This study investigated if higher reported mental imagery vividness leads to a lower performance in a design module, as indicated in Chapter 4. The results of the two modules were compared to confirm that the experience of mental imagery in engineering design differs between individuals and therefore requires further investigation towards making generalisations about the experience. The position of the study in the FMIR falls in the overlap of dimensions of imagery ability (Dv) and imagery modalities (Mv) as the PSIQ measures vividness across different modalities.

7.2 Methodology

The study was conducted with the 2024-2025 cohort of the DM300 Design Emotion and Experience module at the University of Strathclyde, detailed in Chapter 4. The PSIQ was

given to all module members and had a 49% response rate, with 31 out of 63 students completing the questionnaire and opting into the study. The DM300 module is taught to third year PDE, PDI and SDE students, and of the 31 that opted in, 11 were on the PDE course (35.50%), 17 were on the PDI course (55%), and 2 on the SDE course (6.50%). There was one participant who completed the PSIQ who was an exchange student on a course similar to PDI and who was permitted to take part due to the similarities in course content.

In addition to the DM300 cohort, the PSIQ was distributed to the DM983 Design Form and Aesthetics module, also taught in the DMEM department. DM983 is a fifth-year postgraduate module for engineering design students on courses including PDE, PDI and SDE, and Masters (MSc) level courses, such as Design Engineering and Product Design. The module aims for students to develop a knowledge of design form and aesthetics through theory and practice and requires them to produce a project portfolio using their own aesthetic choices and preferences. The module was deemed an appropriate choice for the study due to its focus on physical design through form and aesthetics. The PSIQ was given to the entire DM983 2024-2025 cohort, with 12 responses total, and one of these being removed after failing to complete the module. This total of 11/26 equates to approximately 42% of the class, and the course split was PDE 4/11 (36.50%), PDI 1/11 (9%), SDE 1/11 (9%), and various MSc level courses 5/11 (45.50%).

The format and settings for the new investigation largely remained the same as that detailed in Chapter 4. An online questionnaire was distributed to participants via email, this time to all students in both modules. The study was undertaken towards the end of the semester, before students had their final project hand-ins so as not to impact their studies, and after they had become familiar with the learning material. Participants were not given any set method of answering the questionnaire, found in Appendix 10, and the average response time was approximately seven minutes and six seconds.

As previously, the PSIQ was used as the primary form of measurement for mental imagery vividness. For the new investigation this was adapted to remove the smell and taste modalities as these were not deemed relevant to the design process for the two modules in question, and the results of these modalities in Chapter 4 were negligible enough to justify the removal. The appearance modality (Ap) remained as a necessity as the vividness of visual mental imagery is seen as important in design. As the project for the DM300 module is a sound-based device, the sound modality (So) was left in the PSIQ, especially given that music

has been found to influence mental imagery (Taruffi and Küssner 2019). The vividness of both the touching (To) and bodily sensation (Bs) modalities may have had an effect on module performance as both can feature heavily in design projects through physical interaction with models and designs, for example, and so both were included in the PSIQ. Finally, as both modules feature an emotion or aesthetics theme, the feeling modality (Fe) remained to measure emotion mental imagery vividness. The full questionnaire can be found in Appendix 10, and the questions per modality are as follows:

Appearance:

1. *A friend you know well*
2. *A cat climbing a tree*
3. *A sunset*
4. *The front door of your house*
5. *A bonfire*

Sound:

1. *An ambulance siren*
2. *Hands clapping in applause*
3. *The mewling of a cat*
4. *The sound of a car horn*
5. *The sound of children playing*

Touching:

1. *Warm sand*
2. *A soft towel*
3. *The point of a pin*
4. *Icy water*
5. *Fur*

Bodily sensation:

1. *Relaxing in a warm bath*
2. *Having a sore throat*
3. *Threading a needle*
4. *Jumping into a swimming pool*
5. *Walking briskly in the cold*

Feeling:

1. *Excited*
2. *Relieved*
3. *Furious*
4. *In love*
5. *Scared*

The measurement system used for the PSIQ remained the same for the questionnaire, which is to ask the participants to rate each scenario on a 0-10 scale, interpreted as possible aphantasia to possible hyperphantasia. For the study, the results were referred to as aphantasic (scores less than 1.00), very low vividness (scores between 1.00 and 2.00), low vividness (scores between 2.00 and 4.00), moderate vividness (scores between 4.00 and 6.00), high

vividness (scores between 6.00 and 8.00), very high vividness (scores between 8.00 and 9.00), and hyperphantasic (scores greater than 9.00).

The final grades for both modules are out of 100, meaning that comparisons can be made on the basis of what percentage of 100 the participant is graded. For the purpose of analysis, the DM300 results have been detailed by the critique grade, final exhibition grade, and the overall module grade. However, comparisons between modules focused solely on the overall module grades. Once the data had been gathered, statistical analysis was performed, considering the PSIQ results, by and between participants to determine their vividness levels and how these differ between modalities and individuals, as well as the correlations between vividness scores and final module grades.

Additional questions were asked of the participants on subjects including synaesthesia, memory, imagination, mental imagery control, dimensions of imagery, and imagery translation. However, these questions have the exclusive aim of determining relevance in further studies and are not included in the analysis of the present investigation.

7.3 Results

7.3.1 Design Emotion and Experience

PSIQ results

The DM300 module cohort returned averages of only very high, high, and moderate mental imagery vividness levels. 7/31 participants had a mean score of very high (23%), 13/31 of high (42%), and 11/31 of moderate (35%), with no aphantasic, low vividness or hyperphantasic mean results (Figure 7.1). Of the 11 that participated that are on the PDE course, three scored an average of very high (27%), six an average of high (55%), and two an average of moderate (18%). For those on the PDI course, two scored very high (12%), seven scored high (41%), and eight scored moderate (47%). Finally, the two participants on the SDE course scored one each of very high and moderate, equating to 50% each of the total, and the participant from the course outside of the United Kingdom scored an average of very high. The breakdown by course shows that of the seven who scored a mean of very high vividness, three were on the PDE course (43%), two on the PDI course (29%), one on the SDE course (14%), and one from a course outside of the University (14%). Those who scored a high

average vividness were only on the PDE or PDI courses, with the breakdown being 6/13 (46%) and 7/13 (54%) respectively. 11 out of 31 participants scored an average of moderate, two of these were on the PDE course (18%), eight on PDI (73%), and one on SDE (9%).

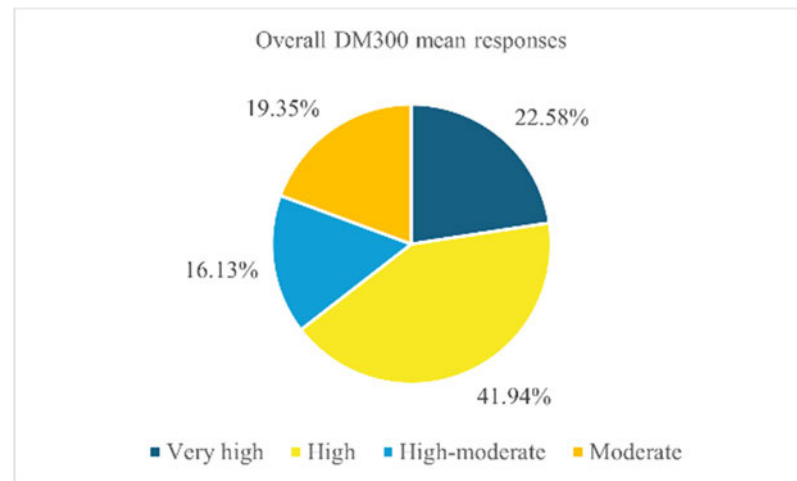


Figure 7.1: DM300 PSIQ mean responses by percentage

Regarding the results of the individual participants, there were a number of outliers or results of note in the PSIQ responses. Participant two (P2) scored Bs Q1 a 9.00 then Bs Q3 a 2.00, leading to a range of 7.00, with their overall ranges per modality varying from 4.00 to 7.00. This variation of responses can be seen in Table 7.1 which depicts P2's total responses and clearly shows the diversity in their imagery experiences. P3 responded with mostly moderate scores for their PSIQ questions, with the exception of outliers, such as scoring 8.00 for To Q1. The main point of interest for P3 is the high number of very high responses for Ap, which features two 10.00 scores. P3's overall responses ranged from 2.00 to 10.00 and their means per modality ranged from 4.60 to 8.60, depicted in Figure 7.2. Another participant of note is P4, whose So responses resulted in an 8.40 mean, but the Fe responses resulted in a 2.20 mean (Table 7.2). Figure 7.3 depicts the vast variation in P6's responses to the PSIQ questions. P6's means range from 2.60 to 10.00, with both their To and Bs means scoring very low vividness and 2.60. On the other hand, they scored the Ap questions all 10.00 suggesting potentially hyperphantasic imagery vividness in the category. This is similar to P11's responses, which are displayed in Figure 7.4, and who returned a mean of 1.20 in the Fe category, but a 10.00 in Ap, with their ranges per modality being as low as 0.00 and as high as 10.00. 88% of P19's scores were in the very high or hyperphantasic category, with 76% of these being rated at 8.00 or 9.00 on the vividness scale. P23 returned 64% of their questions

as hyperphantasic (10.00), and finally, P28 scored their questions mostly moderate, at 68%, but returned 24% of responses as very high.

Modality	Q1	Q2	Q3	Q4	Q5
<i>Appearance</i>	10.00	5.00	8.00	7.00	4.00
<i>Sound</i>	9.00	8.00	9.00	10.00	3.00
<i>Touching</i>	6.00	4.00	4.00	8.00	6.00
<i>Bodily sensation</i>	9.00	6.00	2.00	5.00	5.00
<i>Feeling</i>	7.00	8.00	10.00	10.00	3.00

Table 7.1: P2 total responses for PSIQ

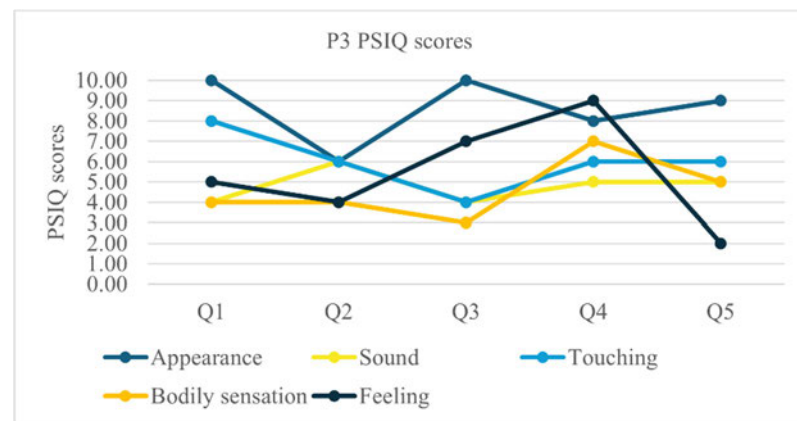


Figure 7.2: P3 overall responses for PSIQ graph

Modality	Q1	Q2	Q3	Q4	Q5
<i>Appearance</i>	6.00	4.00	7.00	9.00	6.00
<i>Sound</i>	8.00	10.00	8.00	10.00	6.00
<i>Touching</i>	8.00	7.00	6.00	5.00	7.00
<i>Bodily sensation</i>	4.00	6.00	6.00	8.00	7.00
<i>Feeling</i>	2.00	3.00	1.00	3.00	2.00

Table 7.2: P4 total responses for PSIQ

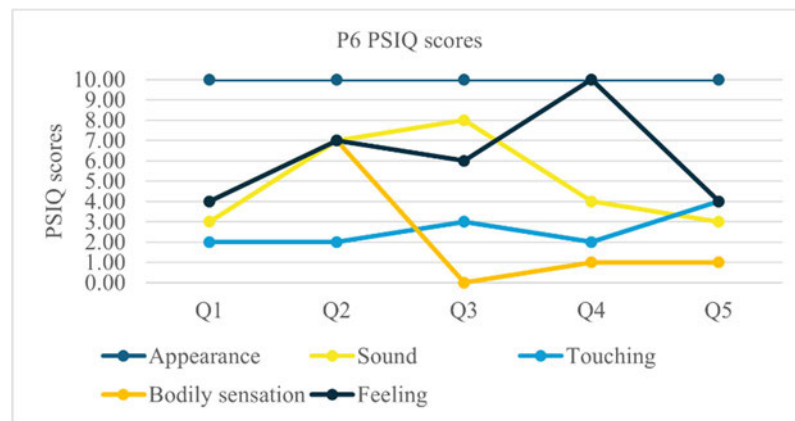


Figure 7.3: P6 overall responses for PSIQ graph

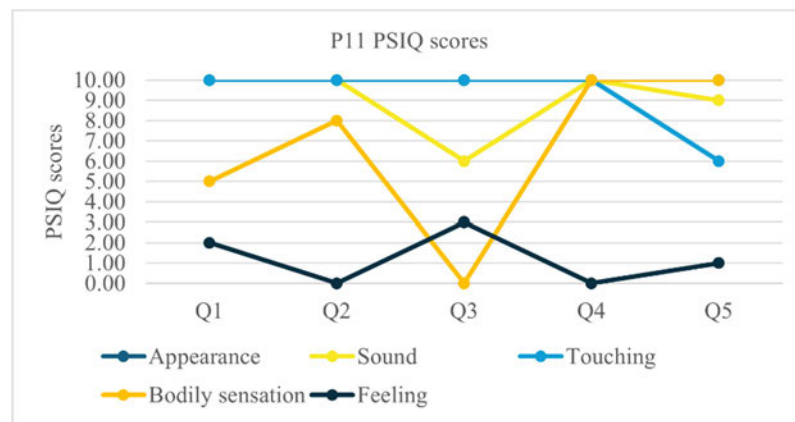


Figure 7.4: P11 overall responses for PSIQ graph

Of the 775 total scores (25 per 31 participant), less than 1% were aphantasic (1.00), and only 26% of all 775 total responses were less than moderate vividness. 73% of all responses were at the moderate levels of vividness or above of 4.00 to 10.00, with 46% of these being scores 8.00 to 10.00, or very high to hyperphantasic. Of the extremes of aphantasic and hyperphantasic, only 6/775 were scored at 0.00 (1%) while 116/775 were scored 10.00 (15%). The full table of responses can be found in Appendix 11.

Statistical analysis has been undertaken to compare the PSIQ responses between the 31 participants. The mean, mode, median, range and standard deviations have been calculated for each modality across all 31 individuals, and the mean result per individual has also been calculated. Of the mean results per participant, none of these were scored between 0.00 and 4.00, or at 10.00. The mean response per modality are all similar and mostly fall into the high vividness level, with the exception of Fe, which returned a mean of 6.23, a moderate vividness level. The overall mean for participants across all modalities is 6.92, a high vividness level

score. The mode across modalities are more varied and range from 10.00 for Ap to 5.00 for Fe, while the medians are fairly consistent, again returning mostly high levels, with the exceptions of 6.20 (moderate) for Fe and 8.00 (very high) for Ap. The overall modality ranges are between 6.00 (Ap) to 8.80 (Fe). Finally, the standard deviations are all consistent over the modalities and between 1.5422 (Bs) to 1.9925 (Fe). There are two participant outliers of note: P4 scored 2.20 for Fe, but 8.40 for So, while P11 scored 1.20 for Fe and 10.00 for Ap.

PCCs were calculated between modalities to compare possible correlations between participant scoring in each modality. The resulting coefficients were largely positive or strong positive correlations, with the exception of So versus Fe which returned a weak positive correlation of 0.0836. So returned three strong positive correlations with To, Bs and Fe, and the strongest correlation was So versus Bs at 0.7208. Table 7.3 depicts all correlations between modalities.

<i>Pearson</i>	<i>Sound</i>	<i>Touching</i>	<i>Body</i>	<i>Feeling</i>
<i>Appearance</i>	0.4243	0.4120	0.2011	0.1985
<i>Sound</i>		0.5502	0.5497	0.0836
<i>Touching</i>			0.7208	0.2037
<i>Body</i>				0.3167

Table 7.3: DM300 PCC between modalities

Comparisons

To compare the results of the PSIQ with the module grades from the DM300 module, PCCs were calculated to check for any and all correlations between means and grades. As can be seen in Table 7.4 and the graphs in Figure 7.5, the correlations were largely similar and almost all negative. PCCs have been calculated between the individual PSIQ modality and overall PSIQ means, and the critique, exhibition, and overall module grades. All three correlations for Ap were similarly negative, with Ap versus overall grade being -0.3655. The only positive correlation found was for So versus critique grade which returned a weak positive and almost negligible correlation of 0.0589. To, Bs, Fe and the overall mean all returned negative correlations when compared with the exhibition and overall grades, and weak negative correlations when compared with the critique grades. For the overall PSIQ mean versus the overall grade, the PCC calculated was 0.3796. The strongest negative correlation is for Fe versus exhibition grade at -0.4092 and the weakest is -0.0243 for To versus critique grade. Two outliers to note are that P1 scored a 0.00 for the critique grade and P18 scored a 0.00 for the exhibition grade.

<i>Pearson</i>	CRITIQUE	EXHIBITION	TOTAL
<i>Appearance</i>	-0.1781	-0.3628	-0.3655
<i>Sound</i>	0.0589	-0.1615	-0.1419
<i>Touching</i>	-0.0243	-0.2403	-0.2280
<i>Body</i>	-0.0368	-0.1777	-0.1715
<i>Feeling</i>	-0.1422	-0.4092	-0.4035
<i>Overall</i>	-0.0911	-0.3919	-0.3796

Table 7.4: DM300 PCC between PSIQ scores and module grades attained

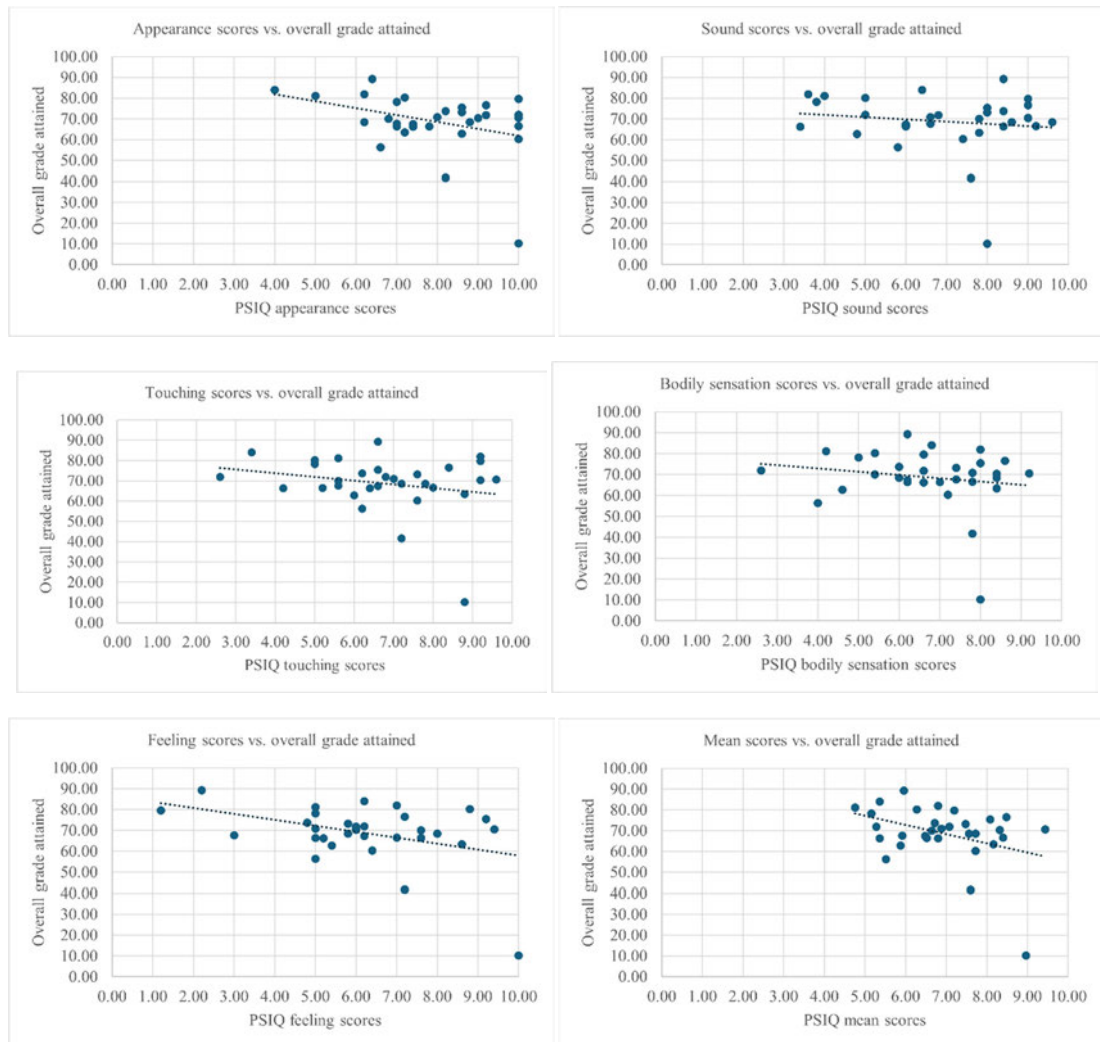


Figure 7.5: DM300 PCC between PSIQ scores and module grades attained

Looking at the results and comparisons by modality, it becomes clear where there are outliers and results of note. Ap, however, returned no outliers and all PCCs calculated were negative. The PCCs, the graphical interpretations of which can be seen in Figure 7.5, are varied, with both positive and negative correlations, and a large number of clustered results.

The overall So mean returned a weak positive correlation of 0.0589 with the critique grade, a negative correlation of -0.1615 with the exhibition grade, and a weak negative correlation of -0.1419 with the overall grade. There were also stark differences between the responses per So question. For example, Q1 versus the critique grade returned a positive correlation of 0.1996, while the exhibition and overall grade correlations for Q1 both returned weak negative correlations of -0.1325 and -0.0935 respectively. Additionally, all total grade correlations were weak negative and depicted as clustered results, except for Q5 which returned a negative correlation of -0.1756.

In the To category, P6 stands out as scoring all low vividness, including three very low scores of 2.00, while P31 is notable by their range from 2.00 to 7.00. In terms of individual questions, both Q2 and Q3 have scores ranging from a low of 2.00 to a high of 10.00. The PCCs for To versus grades are overall negative, with a handful of weak correlations. The notable outliers are the weak positive correlation between Q1 and the critique grade of 0.1068, and the positive correlation between Q2 and the critique grade of 0.1988. The overall PSIQ question scores versus the overall grade were mostly negative, with some clustered results, seen in Figure 7.5, and the overall mean score versus overall grade was -0.2280, a negative correlation.

For Bs, P6 returned a range from 0.00 to 7.00 and P11 from 0.00 to 10.00, while Q3 responses ranged from 0.00 to 10.00. Additionally, Q3 responses featured multiple very low scores and 0.00s, with this question returning the only 0.00 scores, with the exception of Fe. Q4 and Q5 both had ranges from 1.00 to 10.00, but only P6 responded with the lowest of 1.00. The PCCs for Bs returned weak correlations, which can be seen in Figure 7.3. The overall PSIQ mean versus the overall grade was a negative correlation of -0.1715. Finally, Fe featured a larger number of lower scores, with individual participant ranges from 0.00 to 2.00, to 0.00 to 9.00.

7.3.2 Design Form and Aesthetics

PSIQ results

With the participants from the DM983 module, there were again no aphantasic, low, or hyperphantasic mean results. 27% of the cohort reported both very high and moderate imagery vividness, while 46% reported high imagery vividness (Figure 7.6). Out of the four

participants on the PDE course, two reported very high vividness, and there was one report each for both high and moderate vividness. The only participant on the PDI course reported high vividness, while the only participant on the SDE course reported moderate. Five participants were on an MSc level course, and while both very high and moderate vividness were reported by one person each, three of the five reported high imagery vividness. There were three mean reports each of very high and moderate imagery vividness: very high was reported by two PDE students and one MSc student, while moderate was reported by one PDE, one PDI and one MSc student. Finally, one PDE student reported high imagery vividness, as did one PDI student and three MSc students. The results can be found in Figure 7.7.

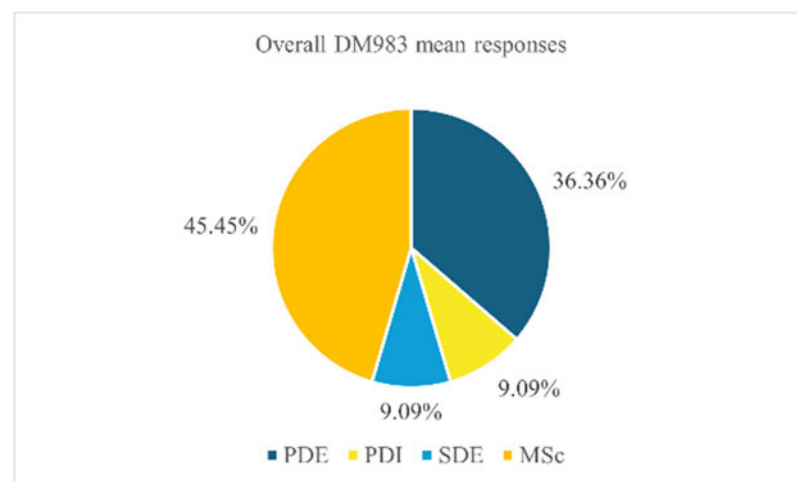


Figure 7.6: DM983 PSIQ mean responses by percentage

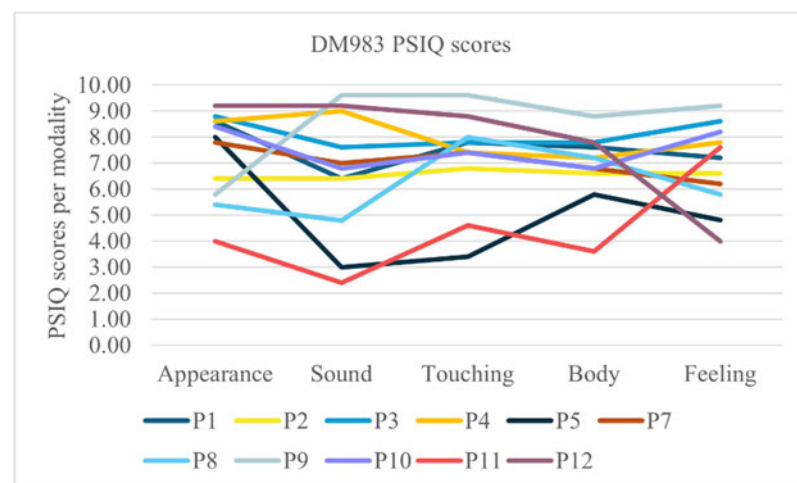


Figure 7.7: DM983 overall PSIQ scores

There were many individual participant outliers in the PSIQ results, for example, participant three (T3) reported majority 8.00 and 9.00 scores, with only one 10.00 for Ap Q4 and one moderate for So Q3, as seen in Figure 7.8. T5's responses were more varied and lacked any consistency, as seen in Figure 7.8. T5's mean results per modality range from 3.20 to 8.00 and they reported a range of up to 8.00, with scores from 0.00 (aphantasic) to 10.00 (hyperphantasic). For Ap, they reported three scores at 10.00 but a 2.00 for Q5; for both So and To their scores ranged from 0.00 to 7.00; for Bs they reported a 2.00 for Q1 but a 10.00 for Q5; and for Fe they reported scores ranging from 2.00 (Q3) to 8.00 (Q1). Both T9 and T12 reported high all-round scores with multiple 10.00 responses each (44%); T12 then reported all 4.00 responses for Fe which can be seen in Table 7.5. T11 had much lower vividness reports with a low-moderate overall mean of 4.44 and a lowest mean of 2.40 (S).

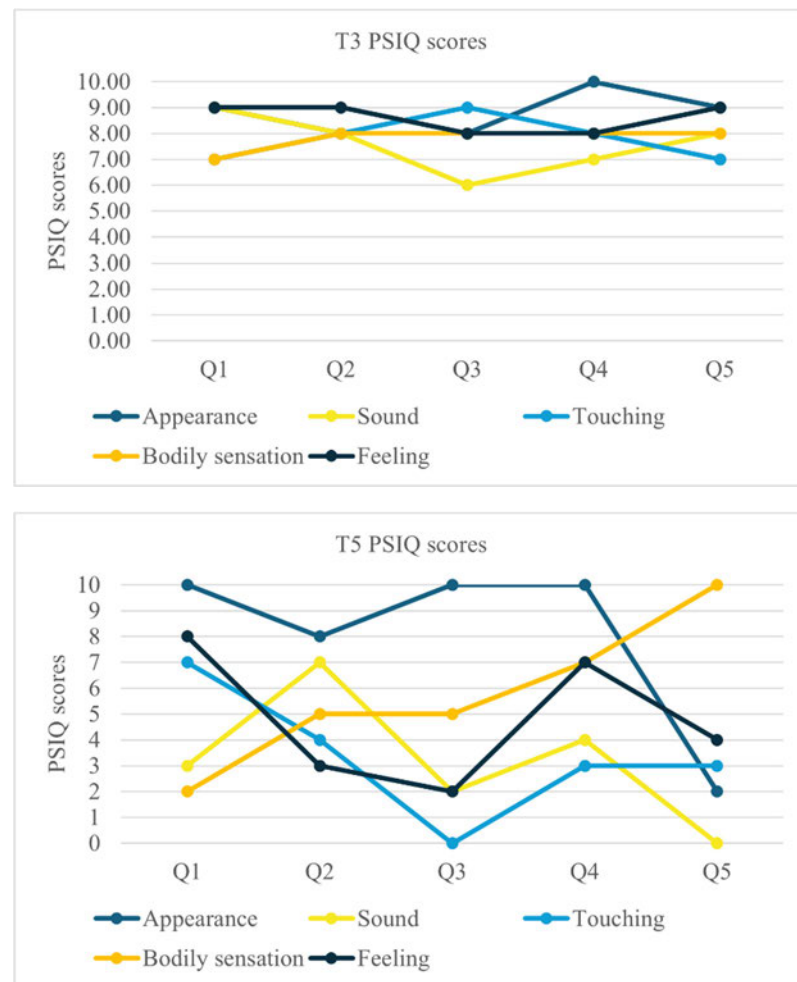


Figure 7.8: T3 and T5 overall responses for PSIQ graphs, respectively

Modality	Q1	Q2	Q3	Q4	Q5
<i>Appearance</i>	10.00	10.00	9.00	7.00	10.00
<i>Sound</i>	10.00	10.00	10.00	6.00	10.00
<i>Touching</i>	10.00	10.00	9.00	8.00	7.00
<i>Bodily sensation</i>	7.00	10.00	10.00	6.00	6.00
<i>Feeling</i>	4.00	4.00	4.00	4.00	4.00

Table 7.5: T12 responses for PSIQ

The total number of responses is 275: 11 participants with 25 responses each. The total responses can be seen in Appendix 12. The most common score was 8.00 which made up 24% of responses (67/275), and 52% of responses (142/275) were scored 8.00 to 10.00 (very high and hyperphantasic vividness). While 82% of scores were 5.00 and above (226/275), only 18% were below 5.00 (below moderate), equating to 49/275 scores. Looking at the mean results per participant, none of the participants reported a mean of 3.00 (low) or below, or of 10.00 (hyperphantasic), while one participant each reported a mean of 4.00, 5.00, 6.00 and 9.00. 73% of participants reported a mean of 7.00 (high vividness) or above, with two reporting 8.00 (very high vividness).

Again, statistical analysis was undertaken and the results returned mean responses ranging from 6.56 (So) to 7.36 (Ap), with 73% means of 6.50 (high vividness) and above. The mode responses ranged from 4.60 (So) to 8.60 (Ap) and the median responses from 6.80 (So) to 8.00 (Ap), with Ap returning the only very high mode and median. The data ranges per modality were as low as 5.20 (Ap, Bs and Fe), and as high as 7.20 (So), while the standard deviations were all between 1.3457 and 1.7651, with the exception of So (2.3796). Two participant outliers were noted for T9 and T11, with T9 reporting a low of 5.80 (Ap) but a high of 9.60 (So and To), and T11 reporting the only low vividness score of 2.40 for So. PCCs were calculated for the data, comparing modalities with each other, as can be seen in Table 7.6. These returned mostly positive or strong positive correlations between data sets, with the only outlier being Ap versus Fe, which returned a negative correlation of -0.1907. The strong correlations were So versus To at 0.8493, So versus Bs at 0.8370, and To versus Bs at 0.8463.

<i>Pearson</i>	<i>Sound</i>	<i>Touching</i>	<i>Body</i>	<i>Feeling</i>
<i>Appearance</i>	0.5007	0.2164	0.4896	-0.1907
<i>Sound</i>		0.8493	0.8370	0.2561
<i>Touching</i>			0.8463	0.2741
<i>Body</i>				0.1603

Table 7.6: DM983 PCC between modalities

Comparisons

For the DM983 module, only the final grades were gathered for comparison with the PSIQ responses, and, again, PCCs were calculated. The results of these can be seen in Table 7.7 and Figure 7.9. The correlations were all negative, with Ap and So returning weak negative correlations with the final module grades. Ap was -0.0003 which is close enough to zero to be negligible, and the graph in Figure 7.9 shows clustered data with no correlation. To, Bs and Fe all returned stronger negative correlations, with Fe being the strongest correlation at -0.3811. The overall mean PSIQ responses per participant compared with their overall module grade returned a PCC of -0.2390.

<i>Pearson</i>	TOTAL
<i>Appearance</i>	-0.0003
<i>Sound</i>	-0.1287
<i>Touching</i>	-0.2231
<i>Body</i>	-0.1924
<i>Feeling</i>	-0.3811
<i>Overall</i>	-0.2390

Table 7.7: DM983 PCC between PSIQ scores and module grades attained

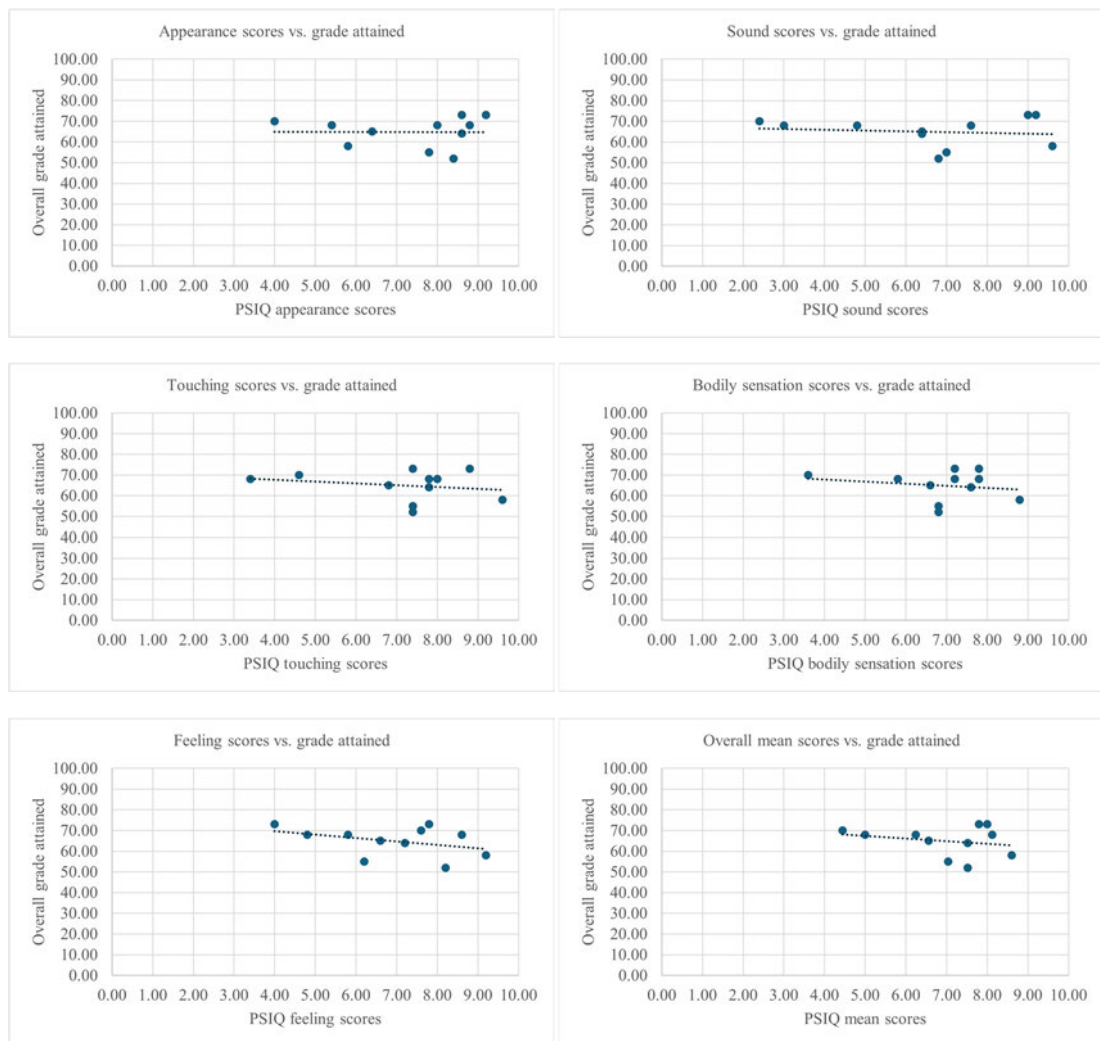


Figure 7.9: DM983 PCC between PSIQ scores and module grades attained

The results for the Ap modality showed much more varied responses from participants. Q4 returned a range of 3.00 to 10.00, with multiple participants scoring 10.00 (hyperphantasic). Q5 has the only 2.00, low imagery vividness, or below from T5. The PCCs for Ap are also more varied, with Q1 and Q3 returning weak negative correlations, and Q2 a weak positive correlation. Q4 versus module grade returned a negative correlation of -0.2471, while Q5 gave a positive correlation of 0.2529.

With ranges per question of 7.00 to 10.00, So is another varied set of responses from participants. P5 answered with a 0.00, 2.00, 2.00, 4.00, and 7.00, while P12 scored questions one 6.00 and four 10.00s. Additionally, Q5 was scored by participants as low as 0.00 (aphantasic) and as high as 10.00 (hyperphantasic). The PCCs were also varied, with Q1 returning a positive correlation with the overall grade of 0.1752, Q2 and Q3 a weak negative

and weak positive correlation respectively, and Q4 and Q5 negative correlations of -0.4122 and -0.2989 respectively. The overall So means per participant compared with their module grades returned a PCC of -0.1287 as can be seen in Figure 7.9.

For To, the responses to Ap range from 0.00 to 10.00 and the lowest range for any question is 6.00 for Q5. All PCCs are negative, except for Q5 which has an almost negligible positive correlation of 0.0701. Similarly consistent is Bs, for which Q2 has two 10.00 responses, and only Q1 has a score of 2.00 or lower. Here, the PCCs are all negative, with the exception of Q3 which has a positive correlation of 0.3319. Again, Fe returned fairly consistent outcomes, with Q3 responses ranging from 2.00 to 8.00. Q3 also returned the only moderate level mean at 5.91, with the rest all returning high level means. The PCCs for Fe were mostly stronger negative correlations, with Q3 returning a weak negative correlation of -0.1136 and Q5 a weak positive correlation of 0.0394. The strongest PCC calculated was of Q2 versus the overall grade of -0.5098.

7.3.3 Comparative results

PSIQ results

The results of the two sets of participant data, modules DM300 and DM983, have been compared for overall results. Statistical analysis has been undertaken on the PSIQ results to compare both sets of data with each other, and to gain an understanding of the total results of all participants together. The mean, mode, median, range and standard deviation of both sets of data were compared, then the same set of statistical data was found for the overall values. The means, as seen in Figure 7.10, were similar across both sets of data, with DM300 returning an overall mean of 6.92, DM983 of 6.99, and an overall participant mean of 6.94. All mean results fall within the high vividness level scores, except for Fe for DM300 and the Fe mean, both of which returned moderate vividness level results. The mode values were very high across most modalities, with the only exceptions being that the DM300 mode for Ap and the overall mode for Ap were both 10.00 (hyperphantasic), and the To and Fe modes for DM300 were both moderate level vividness scores. The median results were largely in the high vividness category, with the DM300 median being 7.00, DM983 8.00, and overall 7.00. Again, Fe for DM300 is the exception at 6.00 and moderate level vividness. The ranges for the data were all very high, with DM300 from 6.00 (Ap) to 10.00 (Bs and Fe), DM983 from 8.00 (Ap,

Bs, and Fe) to 10.00 (So and To), and the overall from 8.00 (Ap) to 10.00. Finally, the standard deviation of the data was mostly within 2.00 to 2.56, the exception being that DM300 Ap had a standard deviation of 1.89 and DM983 So of 2.84. The overall results returned standard deviations of 2.01 (Ap), 2.44 (So), 2.16 (To), 2.22 (Bs), and 2.46 (Fe).

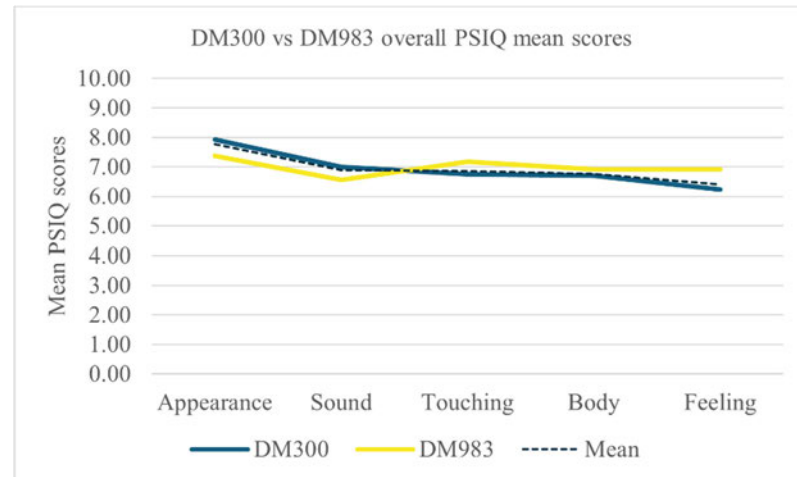


Figure 7.10: Overall mean PSIQ scores

There was a total of 1,050 responses, with 775 from DM300 and 275 from DM983, all of which can be found in Appendices 13 and 14. Of the extremes of aphantasic and hyperphantasic scores (0.00 and 10.00 respectively), only 1% of the total 1,050 responses were 0.00, compared with 1% of DM300 responses, and 1% of DM983 responses. At the other extreme, 14% of responses were 10.00 (hyperphantasic), with 15% of DM300 responses 10.00, and 13% of DM983. Mean results were calculated for both the DM300 and DM983 participants, as well as the overall mean for the study for all 42 participants (31 DM300 and 11 DM983). As with both the DM300 and DM983 results, there were no overall study PSIQ mean results of 3.00 (low) and under, or of the extremes of 0.00 (aphantasic) and 10.00 (hyperphantasic). 30% total participants scored an overall mean within the moderate category, compared with 31% of DM300 and 27% of DM300. Only one participant scored the lowest moderate score of 4.00. There were 26% of participants who returned a mean result of high vividness level, compared with 29% of DM300 participants and 18% of DM300. The highest percentage of participants scored a very high vividness level, at 41%, which was mirrored for DM300 and DM983 participants at 35% and 55% respectively. Despite this, only three participants, two from the DM300 cohort and one from DM983, scored the highest mean recorded of 9.00. The largest single mean score was 8.00, which was reported by 33% (14/42) participants.

The mean score for each modality was calculated for every participant from both cohorts, and the PCC was calculated comparing every modality for all 42 participants. The results were consistent across the modalities, as can be seen in Table 7.8, and show mostly positive correlations. For all three of DM300, DM983 and the total, So versus To, So versus Bs, and To versus Bs all show strong positive correlations of over 0.6000, with To versus Bs returning the highest PCC across the three calculations. Ap versus Fe had the most variations in PCCs, with DM300 returning a positive correlation of 0.1985, DM983 a negative correlation of -0.1907, and an overall of only 0.0814, an almost negligible positive correlation. Overall, all ten PCCs calculated for the total participants were positive, with two of these being weak, and three being strong.

<i>Pearson</i>	<i>Sound</i>	<i>Touching</i>	<i>Body</i>	<i>Feeling</i>
<i>Appearance</i>	0.4551	0.3349	0.2559	0.0814
<i>Sound</i>		0.6194	0.6084	0.1076
<i>Touching</i>			0.7487	0.2314
<i>Body</i>				0.2925

Table 7.8: Overall PCCs between modalities for combined cohorts

Comparing PSIQ results with module grades

The final grades for both the DM300 and the DM983 modules were scored out of 100 allowing for easy comparisons between the results. As previously, PCCs were calculated for the full cohort of both modules together to compare with the individual module results, and this was done for each PSIQ modality and the overall mean score. As can be seen in Table 7.9 and Figure 7.11, the calculations returned all negative correlations, with the only exception being one negligible correlation for DM983 versus Ap. The remaining PCCs range from -0.1715 (Bs versus DM300) to -0.4088 (Fe versus total). So is the main exception, with all results returning weak correlations of -0.1419 (DM300), -0.1287 (DM983) and -0.1156 (total). The overall PCCs calculated for the PSIQ overall mean scores versus the final grades for all participants were -0.3440, compared with -0.3796 for the PSIQ overall mean score versus module grades for the DM300 participants, and -0.2390 for the DM983 participants.

<i>Pearson</i>	DM300	DM983	Total
<i>Appearance</i>	-0.3655	-0.0003	-0.2696
<i>Sound</i>	-0.1419	-0.1287	-0.1156
<i>Touching</i>	-0.2280	-0.2231	-0.2318
<i>Body</i>	-0.1715	-0.1924	-0.1776
<i>Feeling</i>	-0.4035	-0.3811	-0.4088
<i>Overall</i>	-0.3796	-0.2390	-0.3440

Table 7.9: PCCs between overall PSIQ scores and module grades attained

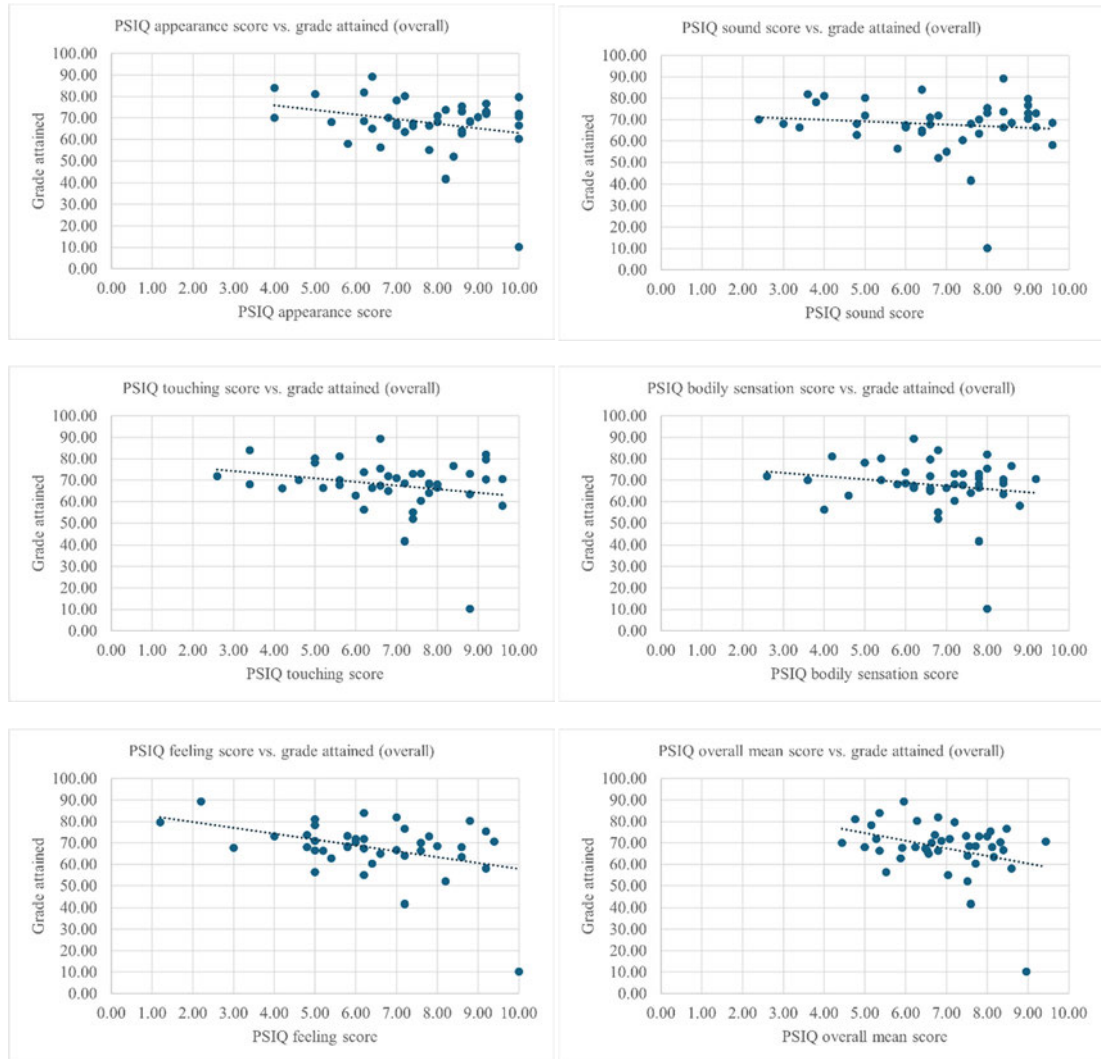


Figure 7.11: Correlation graphs between overall PSIQ scores and grades attained

7.4 Mental imagery in design education

7.4.1 PSIQ results

Mental imagery vividness across the participants, appears to be high on average, with an overall mean of 6.94 across all participants. While it is difficult to give a definitive reason for this, it is commonly believed that mental imagery is a common experience for most designers (Pearson 2007), so it is not particularly surprising that two cohorts of design students report an average of high mental imagery vividness when measured by a psychometric questionnaire. There were few notable differences in the mental imagery responses by specific course, and as the study is not measuring course impact, these will not be investigated further.

A range of different means were calculated for all three groups of DM300, DM983 and overall totals including for each modality per person, for each modality in total, and overall mean per individual. The resulting calculated means were similar across all three groups, which, again, could be explained by the fact that the participants are all students on engineering design courses and may be experienced with accessing their mental images in design. There were no means per participant of aphantasic (0.00), very low or low (1.00-3.00), or hyperphantasic (10.00), and only one participant scored a mean of under 5.00 (moderate). This is interesting as it clusters all participants into the category of moderate to very high mental imagery vividness. The mean results are somewhat consistent across the overall total, DM300 and DM983 cohorts, with the exception of Fe. This mean is lower for both DM300 and the total, both of which sit at a moderate level, while all other mean results are in the high category. Given that DM300 is an emotion-focused module, it is surprising that participants would score their feeling emotion lower and raises questions about why this might be the case. One potential reason is that the specific questions are impacting on how the participants are responding, such as feeling “in love” which is a highly subjective experience that not everyone may have had experience with. Of the total participant means, 30% were moderate level vividness, 26% were high, and 41% were very high, emphasising the consistency across modalities. One notable result comparison is the mean very high modalities in the DM983 cohort being 55% compared with the DM300 cohort being only 36%. DM983 students are further along in their studies so it raises the question of if more experienced students have a better understanding of their mental imagery. Both DM300 and DM983 have combined means of high or very high of over 50% and 70% respectively, so the imagery vividness in each

module is strong on average, despite DM300 having more diversity in means than DM983, for example, with Fe being moderate.

Of the total 1,050 scores, the extremes of aphantasic only made up 1% while hyperphantasic 14%. These results are consistent across the three groups, and given the higher vividness averages, it is unremarkable that hyperphantasic events occur more often than aphantasic. There is also the possibility that as these are engineering design students, they are inherently more aware of their mental imagery and able to better describe what they are experiencing, although evidence for this is tentative. Of all responses, only 9% are below moderate, and most of the response percentages are consistent across the three groups, which suggests that either mental imagery is relatively consistent, or the students are. Of note in the analysis of the total scores are that very high scores are reported 33% of the time overall, with DM300 reporting 31% of scores and DM983 39%. This jump of over 8% between DM300 and DM983 is interesting and potentially reinforces the argument for more experienced design students having more vivid mental imagery, or a better understanding of their own cognition. Over half of the DM300 cohort reported scores of greater than or equal to moderate level vividness, and over 45% above 8.00 (very high), while DM983 has over 50% at very high or hyperphantasia, and less than 18% at less than 5.00 (moderate).

The mode and median results are also consistent across DM300, DM983 and the total. Again, however, Fe stands out in the median results as an outlier with a moderate median compared with all others being high. Potential reasons for this are discussed further in this Chapter, but it is an interesting outlier, especially given that feeling is emotion based, rather than sense based, as with the rest of the modalities measured. The results show a great deal of diversity in the mental imagery experience, and the ranges calculated add to this evidence. All of the ranges calculated are high, with DM300 returning slightly higher ranges than DM983. Specific interesting examples include P3 in DM300 with a range of 2.00-10.00, and T3 in DM983 showing high consistency in their scoring compared with T5's lack of consistency. The individual varied ranges are evidence that the mental imagery experience is diverse and varies greatly from person to person. The standard deviation results are all over 2.00, which is relatively high and suggests more variation from the mean, but all standard deviation calculations returned consistent results. This emphasises the consistency seen throughout the statistical analysis and the diversity in mental imagery.

Of the PCCs calculated, there were a number of weak correlations, most of which can be disregarded since they signify no true correlation and there are minimal comparisons to be made with them. The remainder of the PCCs were mostly positive across all three groups of DM300, DM983 and the total, with a large number of strong positive correlations. So in particular returned many positive correlations, suggesting that it has a particular connection to the vividness of other modalities, which could be theorised as being connected to the impact music has on mental imagery (Taruffi and Küsser 2019), but would require further investigation to confirm or disprove. Once again, Fe appears to be an anomaly in that it returned much more varied PCCs. The Ap versus Fe PCCs stand out as anomalies, with the PCC for the total data set being 0.0814, for DM300 being 0.1985, and for DM983 -0.1907. This lack of consistency in one being a positive correlation, one being a negative correlation, and the total seeming to cancel these out for an almost negligible positive correlation is remarkable. Further investigation into the results may help provide a reason for this inconsistency.

7.4.2 Comparing PSIQ results with module grades

The PSIQ results have been compared to the module grades to find correlations between the data sets. This has been undertaken by calculating all modality means and the overall mean for each individual participant and running PCC calculations on each of these against the final module grades. These calculations have been performed for the separate module cohorts and the overall pool of participants. The weak correlations are almost negligible suggesting these results are more clustered than a true correlation or trend. All weak PCCs have been removed from discussion due to their inability to show a true correlation in the data. As these results show more clustered data, such as the near 0.00 result for DM983 versus Ap, they fail to give a definitive correlation. Additional comparisons have been made for the DM300 cohort by separating their grade into final grade, critique grade and final exhibition grade. The only standout difference in this data is that the critique PCCs are weaker than the other PCCs. While it is interesting to understand how differences occur at different times in the module, the separate calculations have been deemed less important to the final analysis, with sufficient insight provided through final and overall module grade alone.

The PCCs calculated show overall negative correlations between imagery vividness scores and overall module grades in an engineering design module. This suggests that higher

imagery vividness levels lead to lower performance in a design module by the student engineering designers investigated, an interesting outcome given the general assumption that students and professionals in creative industries have more “useful” mental imagery (Pearson 2007). Further investigation may be needed to understand why this is the case, with potential reasons being design fixation, imagery processing issues, such as memory and imagination imagery differences, or individuals having a harder time accessing certain imagery modalities. The DM983 correlations were mostly weaker than both the DM300 and total correlations, with the exception of Bs, but this difference is almost negligible. Possible interpretations of this are that the module itself or their current length of study could be having an impact on how well students perform or their imagery vividness levels are impacting. Further, it is worth querying if a different imagery questionnaire would have given different results, and if the issue is with the questionnaire itself. In Chapter 3 it was noted that individuals did not understand the connection between general psychometric imagery questionnaires, such as the PSIQ, and their relevance to the discussion of mental imagery in design. The results here could be evidence of this, with students having a disconnect between the questions and the study topic itself. Finally, the So modality has the weakest overall correlations for each calculated group of DM300, DM983 and overall participants. One possible explanation is that participants are not utilising their sound imagery during the design process as they have no use for it, counter to what was theorised at the start of this investigation that sound imagery would be a key experience when designing a sound-based device.

7.4.3 Additional research into study topics

Additional questions were put to participants alongside the PSIQ to gather information on which mental imagery elements might be worth investigating in future studies and to measure additional aspects of the mental imagery experience. These questions were asked in a similar manner to the PSIQ and analysed statistically to gain insight into how participants respond to questions about their imagery experience, and if the topic is an important consideration to the mental imagery experience.

The first question covered the topic of synaesthesia, the phenomenon in which individuals experience additional senses to a sense being stimulated (Chun and Hupé 2015). The question asked to participants was

Do you, as far as you are aware, experience synaesthesia (the experience of multiple senses at once, i.e. tasting words or seeing numbers as colours)?

The participants were given the answer options of “yes”, “no”, and “unsure”. The overall breakdown of responses from all 42 participants, which can be found in Figure 7.12, were 33% “yes” (14/42), 45% “no” (19/42) and 21% “unsure” (9/42). The high volume of “yes” responses to the question is surprising given that synaesthesia is thought to impact only a small percent of the population, and so the suggestion that a third of all participants experience the phenomenon is unexpected. It is possible that this is correct, given the subjectivity of cognition, and by coincidence the participants for this study have higher levels of synaesthesia among their population. However, a more realistic explanation is that there is a misunderstanding of what is meant by synaesthesia. This argument can be strengthened through the analysis of the “unsure” responses. With over 20% of participants responding that they were unsure how to answer the question, this indicates that more explanation is needed in order to get a clear picture of if or how participants experience synaesthesia. In conclusion, the topic of synaesthesia is likely not useful for future studies in the current project without overcomplicating the research.

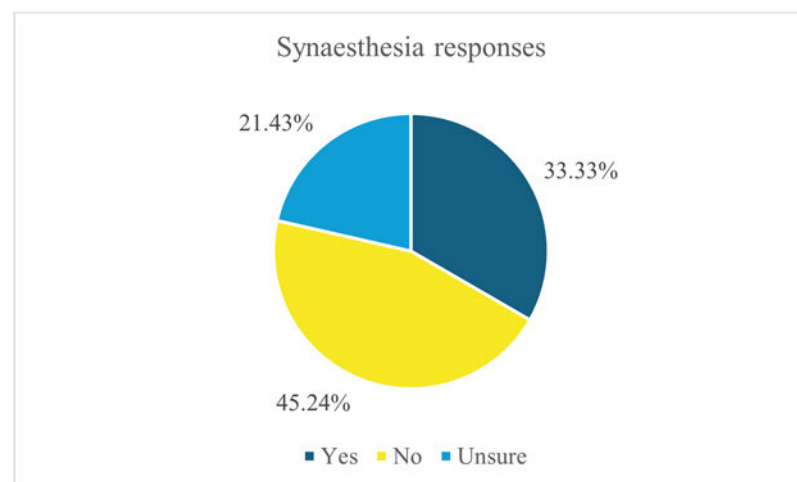


Figure 7.12: Synaesthesia question overall results

The participants were then asked about their memory and imagination imagery, with a view of comparing the results. The memory question asked was as follows:

How would you rate your memory on a scale of 0-10 with 10 being a photographic memory?

Participants were asked to rate their memory on a scale of zero to ten as it would be the easiest to understand having used a similar to scale to answer the PSIQ questions. The results can be found in Figure 7.13. Of the total 42 participants, 19% rated their memory at lower than five (8/42), 62% rated their memory at five, six or seven (26/42), and 19% rated their memory above an eight out of ten (8/42). It is unsurprising that most participants have rated their memory in the moderate area of scores, with none scoring an extreme of photographic memory or no memory at all. While these results allow for an insight into how participants would rate their memory, it would be useful to understand exactly how they experience memory mental imagery, and its comparison with their imagination mental imagery experience.

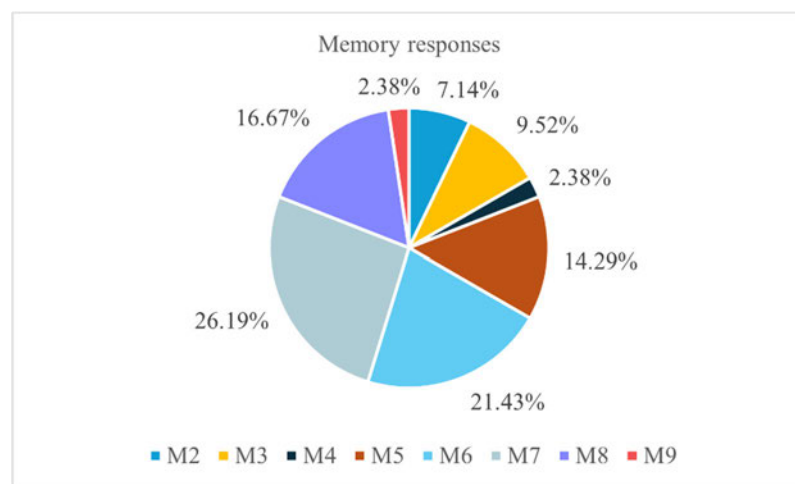


Figure 7.13: Memory question overall results

For the imagination question, participants were again asked to rate their imagination on a scale of zero to ten, with the question:

How would you rate your imagination on a scale of 0-10, with 10 being extremely imaginative?

While the reason for asking the question is the same as with the memory question, imagination is arguably harder to subjectively judge or explain due to differences in how an individual understands or defines imagination. Of the total of 42 participants, 7% rated their imagination below a five (3/42), 38% rated their imagination a five, six or seven (16/42), with 55% of participants rating their imagination an eight or above (23/42). Over 50% of participants report having a very high imagination is not unlikely, seen in Figure 7.14, and one potential explanation is that the participants are all students on an engineering design course, so it could be that they have a better understanding of their imagination, or that they are inherently more imaginative given their path of study. The question of imagination should be included in

further investigations, but it would be beneficial to have follow up questions to help understand how exactly a participant interprets and experiences imagination imagery.

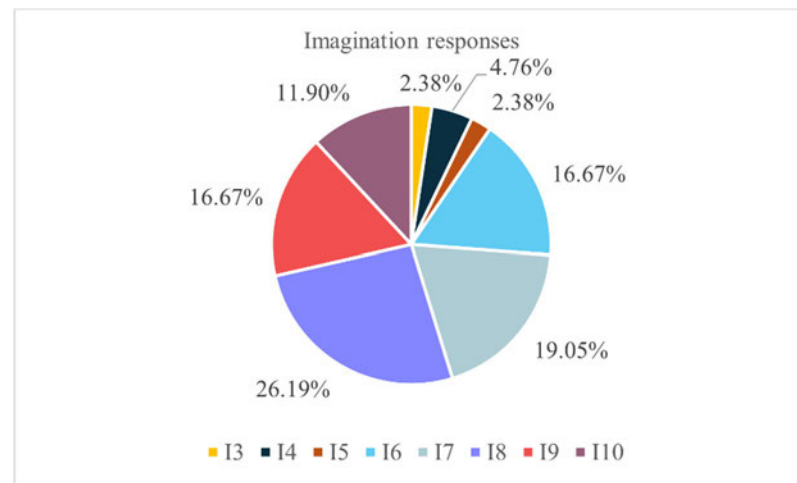


Figure 7.14: Imagination question overall results

The memory and imagination responses have been compared by calculating a PCC for all 42 participants together. The PCC calculated for the total participants is 0.2393, a positive correlation. The calculation, and the graph found in Figure, 7.15 suggest that a higher memory rating may correlate positively with a higher imagination rating, but largely the results appear more clustered than a true correlation. While these results are interesting and are a justification for including questions on memory and imagination imagery in future studies, it would be better to evaluate these responses alongside open-ended questions. Examples include asking participants how their memory imagery occurs during their design work, or if their memory and imagination imagery are connected at all. Further, better explanations and definitions of what we mean by each form of imagery would be beneficial, especially for imagination imagery which is so inherently subjective.

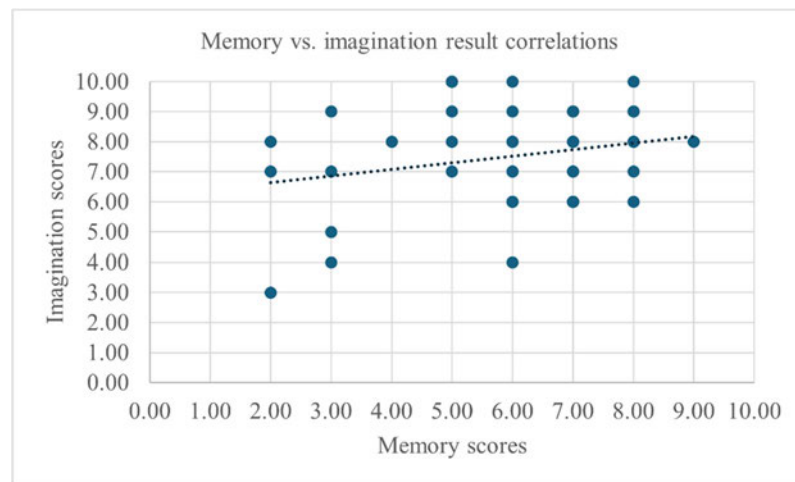


Figure 7.15: Correlation graph for memory versus imagination question results

Participants were asked a question about the intention of their mental imagery and their control of it as a process in order to understand if participants are aware of how and when they experience mental imagery. The question was as follows:

If you experience mental imagery, would you describe it as voluntary, involuntary, both, or neither?

They were asked to select an answer from the following list: “voluntary”, “involuntary”, “both”, or “neither”. Of the total 42 participants, 12% selected “voluntary” (5/42), 14% “involuntary” (6/42), 72% “both” (30/42), and 2% “neither” (1/42). With only one person selecting that they experience neither voluntary or involuntary imagery, this suggests that majority, if not all, of the participants understood what the question was asking of them. Referring back to the findings in Chapter 3, it would be beneficial to ask further questions evaluating what the participants’ understanding of how they experience control of their mental imagery, for example, if they can willingly generate or transform mental images. Again, this topic would be beneficial in future studies to better understand how mental imagery is controlled and processed.

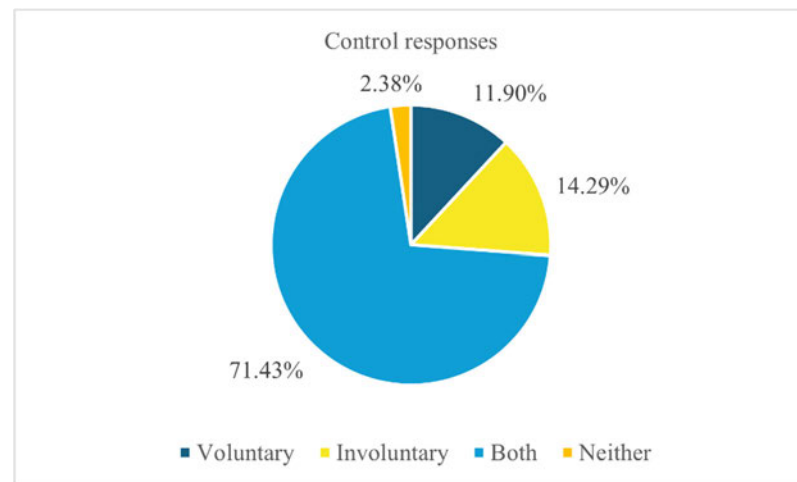


Figure 7.16: Control question overall results

In order to understand how participants experience dimensions of mental imagery in forms other than vividness, participants were asked:

If you experience visual mental imagery, can you visualise in 2D, 3D, both, or neither?

They were asked to select an answer from the following list: “2D”, “3D”, “both”, or “neither”. 7% of the total 42 participants responded that they visualise in “2D” (3/42), 17% responded “3D” (7/42), and 2% responded with “neither” (only 1/42). 74% of the total 42 participants answered that they experience visualising in “both” 2D and 3D, with 31/42 individuals selecting this response. Again, as with the intentionality question, only one participant answered “neither” which suggests that the question was understood, but it would be beneficial to have additional explanations in the future. On top of this, the topic of dimensions of imagery ability should be opened up further to include other areas such as spatial ability, so as to gain better insight of the full mental imagery experience. Including discussions and open-ended questions may help with this by encouraging a dialogue.

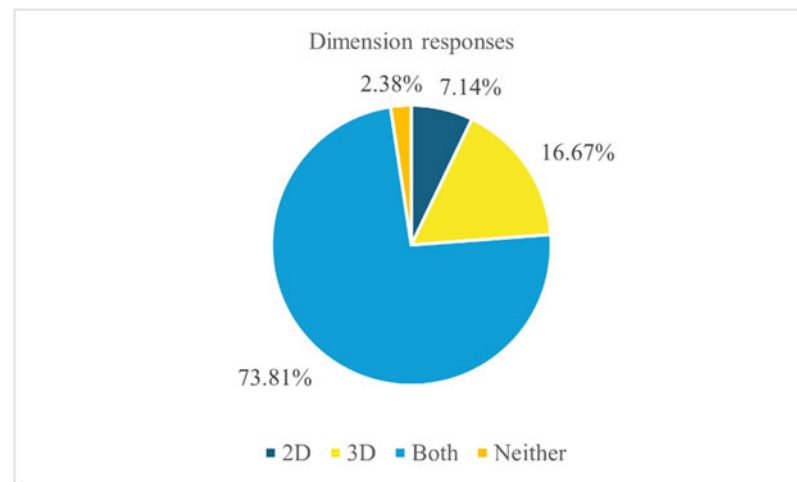


Figure 7.17: Dimension question overall results

The final question asked was:

If you experience visual mental imagery, how easy do you find it to translate the images in your head to paper?

There is an assumption in design that everyone sketches and that this is an easy embodiment of mental imagery, but this may not be the case for everyone. The intent of this question was to investigate how useful it is to understand individual experience of mental imagery translation. It was measured by participants responding: “extremely easy”, “somewhat easy”, “neutral”, “somewhat not easy”, and “extremely not easy”, and the results can be seen in Figure 7.18. The breakdown of the total 42 participants was 10% of participants responded “extremely not easy” (4/42), 12% responded “somewhat not easy” (5/42), 21% responded “neither” (9/42), 40% responded “somewhat easy” (17/42), and 17% responded “extremely easy” (7/42). These results show that almost 60% report that they find it easy to translate their mental imagery into sketches. This topic is deemed important for understanding mental imagery experiences in design, though it requires more information than the answer to a single question. Possible solutions for this could include a different form of analysis or data gathering, such as protocol analysis, where participants can discuss this topic through their design work itself.

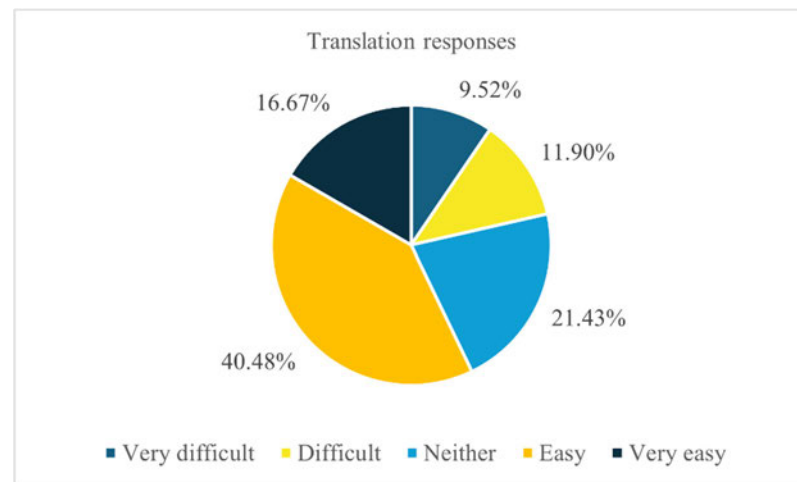


Figure 7.18: Translation question overall results

7.5 Conclusion

The investigation detailed in this chapter has presented conclusively negative correlations between mental imagery vividness reports and grade attainment in specific engineering design modules. The results show that of the engineering design students investigated, those reporting higher levels of mental imagery vividness perform worse in either of the design modules considered in the study. While understanding the reasoning for this was outside of the scope of the study, it has provided evidence of the requirement for further discussion when investigating mental imagery experiences in engineering design students. Simply asking pre-set psychometric questions for measuring their mental imagery vividness to compare to their design outcomes is not enough to fully understand their mental imagery experiences. Additionally, the use of the PSIQ and analysis undertaken on the results add support to the requirement for a design-specific mental imagery measurement questionnaire, something which will be considered in future work on this research project. To conclude, the work detailed in this Chapter will allow for alterations to be made to the next steps in the project, to continue the goal of defining the mental imagery experience in engineering design.

Chapter 8: Visual imagery in the design process

8.1 Introduction

The prior research detailed in this thesis has culminated in the justification to undertake an in-depth research study investigating the experience of mental imagery in engineering design students during their design process. The literature review in Chapter 2 detailed a knowledge gap on how mental imagery is experienced in engineering design, with subsequent studies on mental imagery experiences confirming the complex elements that research into this area could reveal. The overall aim of this study is to show that mental imagery experiences differ between engineering design students and throughout their individual design process. The objectives of the study were to map visual imagery experiences of individual engineering design students, identify unique elements of the phenomenon in the field, and to propose profiles representing the experience of visual mental imagery. This research enabled a definition of visual imagery in engineering designers to be developed alongside a shared understanding for the research field. This represents progress towards defining mental imagery as an entire experience in engineering design.

Using protocol analysis and psychometric measurement, the investigation enabled a detailed mapping of the participants' experiences of mental imagery during and around their design process. Psychometric questionnaires are the customary form of mental imagery measurement, but as has been discussed in previous chapters, those that exist currently do not produce the most reliable results for measuring imagery experiences in engineering design. Creating a new type of questionnaire for the study was the first step in clarifying their use for mental imagery research in design. For design research, measurement of the mental imagery experience needs to rely on more than just vividness measurement. There are many elements to the mental imagery experience, particularly in design, including memory, imagination, and active use. A questionnaire for deciphering this experience should encompass all of these elements.

Despite the benefits of using a psychometric questionnaire, it was highlighted in Chapter 3 that using set measurement questions alone does not provide the best understanding

of the mental imagery experience in design settings. Being able to follow these questions up with discussions and interview-style sessions provides a more holistic view of an individual's mental processing styles. While it is straightforward to use a questionnaire to gather responses then state that an individual's mental imagery vividness level is reported as either a one or a four (low or high respectively), as found in Chapters 3, 4 and 7, the individual may have a different way of describing what they are visualising to someone else, or they may be visualising the scenario using only memory as opposed to imagination, as an example. These discussions also allow for the planning of if a participant experiences aphantasia. While this is not being measured for specifically in this study, it is a necessary consideration given that Chapter 3 presented evidence of designers with aphantasia and including interview sessions would allow for a better understanding of these designers should this occur.

The inclusion of a design session allows for an understanding of the mental imagery experiences of the designers while they are working through their design process. This enables an answer to the question of *how* designers experience mental imagery during the design process, rather than only focusing on what designers report experiencing. Using both protocol analysis and questionnaires, and interviews and discussion sessions allows for both quantitative and qualitative results. This provides a well-rounded view of the participants' mental imagery experiences without relying on either numerical results or subjective reports alone. Protocol analysis is a verified method for measuring mental imagery in design research. It is feasible for the mental imagery experience to be discussed from a participant's physical design output and their interviews alone, but by combining protocol analysis with the think-aloud method (Gero and McNeill 1998; Suwa, Purcell and Gero 1998; Hay *et al.* 2017) and implementing this into the measurement of mental imagery experience, a more rigorous comprehension can be developed. Protocol analysis encourages a designer to process their thoughts aloud, giving researchers a direct insight into the subjective experiences during the design process (Lawrie, Hay and Wodehouse 2022). By then coding these subjective thoughts alongside their actions, researchers can gather quantitative insight into their design cognition (Gero and McNeill 1998; Suwa, Purcell and Gero 1998). While observing design sessions also allows insight into the design process, it relies on a researcher's own subjective judgement, whereas protocol analysis allows for links and connections between thoughts and actions to be created. The use of protocol analysis in the study enabled the participants' experiences to be mapped and analysed. Combining this method with the questionnaires and interviews deepens the understanding of these mapped experiences.

The study, through its combined research approaches, falls into the overlap of all viewpoints of mental imagery in the FMIR (Macfie, Hay and Rodgers 2023). While the investigation primarily covers viewpoints Dv and Pv of the FMIR, Mv does come into relevance due to the focus on and discussion of visual mental imagery, and through the coding for emotion where relevant. For Dv, the study measures and discusses vividness of visual imagery, along with other dimensions of imagery ability, and for Pv, memory, imagination, and intentionality of the imagery experience are all measured and discussed. In addition to this, visuospatial abilities such as imagery generation and transformation are featured throughout, which is contained within the overlap of Dv and Pv. By situating the investigation in the FMIR, the relevance of the study to the research of mental imagery experiences in engineering design has been established.

8.2 Methodology

8.2.1 Participants

A total of 13 participants took part in the study, and no personal identifying information was obtained, aside from necessary contact information and course of study details. The number of participants was capped at 13 students following the pilot sessions, once the volume of data being gathered from each participant was observed. It was determined that a minimum of ten participants, or ten individual mapped experiences, would be satisfactory to achieve the research goals, with 13 allowing for failures. This would avoid oversaturating the data and allow the research to be completed within the timeframe. Participants were gathered through distribution of posters and advertisements across the department, with students self-registering to participate. All participants were offered a £20 store gift card in exchange for up to 90 minutes of their time. As the aim of the study is to show that mental imagery experiences differ between engineering design students, students within DMEM were selected as the participants, with their expertise as engineering design students making them an appropriate choice. It was decided that fourth- and fifth-year students from across the department would be invited to participate as they have appropriate experience of the design process.

8.2.2 Study set up

The study took place in a small meeting room, with minimal distractions and as simple a workspace as possible. Participants were sat at a desk, with access to various design tools, and a laptop camera and microphone were used to record the sessions. The researcher was sat at a distance to not interfere with the session, aside from during question-and-answer periods. All pilot and main session studies took place in the same space with the same set up, and all information, except interview questions, was read from a script to minimise variables.

Consisting of three elements, the study was scheduled to take between 60 and 90 minutes per participant. The shortest session was approximately 55 minutes, and the longest approximately 85 minutes. The study consisted of a questionnaire, a design task, and interviews, all of which were designed to gather detailed information on how the participants experience mental imagery in their design process. While it is acknowledged that this expanded way of measuring mental imagery is still subjective in nature, it enabled a more detailed view of the various elements within a designer's mental imagery experience through discussion.

Various measurement systems were used throughout the session, depending on the component at hand. The questionnaire was measured via different methods for each topic and is detailed further in Chapter 8.2.3. The design task was recorded, transcribed and coded according to coding schemes, as well as measured through the qualitative approach of the researcher's notes from watching each participants' process. This protocol analysis method and coding scheme used are detailed more in Chapter 8.2.4, and Chapter 8.2.6. The interview portions of the session were measured both through the same protocol analysis method, and through a follow-up questionnaire focusing on participants' mental imagery in design, detailed further in Chapter 8.2.5. Prior to the study, participants were asked to complete a pre-existing mental imagery measurement questionnaire via an online survey so that there was a shared understanding of the definition of visual mental imagery. The VVIQ (Marks 1973) (Appendix 13) was selected due to its focus solely on visual mental imagery, as no other modalities of imagery were to be considered in the study.

Due to the nature of the study, some components needed to have more of a discussion nature to them, meaning the researcher could not entirely sit out of the session. In order to minimise the impact of the researcher on the session, they were sat at a distance that meant through periods where they were not to interact actively with the participants, they could do

so easily, but that during the discussion sections of the session, they could comfortably have a conversation. The only session periods that the researcher actively interacted with participants was during the explanations of the upcoming stage of the study, and the interview periods.

The VVIQ was sent to participants via a Microsoft Forms page to allow for easy distribution prior to the session. Entire study sessions were video, and audio recorded on a laptop through the Microsoft Teams recording function, with all participants giving their consent for this to take place. The Microsoft Teams transcription function was used to transcribe all sessions; these transcriptions were then organised by the researcher for clarity and ease of use. All question responses were recorded both through the recording, and through manual note taking by the researcher, with the exception of the interview questions, responses to which were only gathered via the recording. Finally, the researcher took hand-written notes throughout the design task portion of the session on questions to ask in the interviews for clarification of assumptions.

8.2.3 Questionnaire

During the interviews with designers in Chapter 3 it was noted that there was a disconnect between the relevance of the questionnaire topics to the discussion around mental imagery, largely due to the lack of design-focus. Following this, during the studies in Chapters 4 and 7, the PSIQ topics led to varying response understanding due to subjective interpretations of situations, as well as a lack of depth to how mental imagery is experienced in design. One suggestion as a solution to this issue is to develop a psychometric mental imagery questionnaire that focuses on elements of design and how mental imagery is experienced in design. It was decided to include a questionnaire component in this study in order to trial different forms of design-focused questions. These questions were analysed to determine what is relevant or necessary for inclusion in a future psychometric questionnaire.

With the need for a more extensive and focused measurement system in mind, it was decided that the questionnaire should cover a range of mental imagery elements. As this study is the first iteration of new form of measurement in practice, a selection of topics was constructed from the literature review, FMIR, and the questionnaire study in Chapter 3. The full selection includes vividness, perspectives, control, colour, spatial imagery, object imagery, temporal, rotation, combining, generation, transformation, intention, memory, and imagination

imagery. As discussed in Chapter 8.1.2, the study is focusing mainly on Dv and Pv in the FMIR, with some minimal reference to Mv, so for the most part, topics relating to multisensory or emotion imagery can be disregarded for this study and initial questionnaire iteration. The resulting selection of relevant topics were as follows:

- Dv: imagery vividness and perspectives of imagery
- Dv and Pv: imagery control, colour imagery, spatial, object, temporal and rotational ability, and combination, generation and transformation imagery processes
- Pv: intention in mental imagery, and memory and imagination imagery

The final selection of topics for the questionnaire was imagery vividness, intentionality of imagery experience, mental imagery control, and memory and imagination imagery. At the beginning of each section of the questionnaire, participants were provided with a scripted explanation of what is being measured and how, and how they should answer the question. The questions were asked aloud, and participants responded aloud, with no other instructions given.

Measuring the participants' visual mental imagery vividness was a necessary inclusion in the study. Rather than establish a new measurement scale and question format, the VVIQ (Marks 1973) was used as the foundation for most of the questions in the questionnaire. The VVIQ uses a five-point scale to measure mental imagery vividness, from one (no image at all) to five (as vivid as real life). This short scale is simpler, both for the participants to envision when answering the questions, and for data collection and analysis due to the reduced selection of answers. The VVIQ's question format was also followed for this portion of the questionnaire as it is a verified measurement system. As noted, the question subjects were to be design-focused where possible. For the vividness portion of the questionnaire, it was decided that these subjects would be centred around various design features: colour, perspective, form (2D, etc.), action, object detail, texture and surface, pattern, and shape. As the questions were being asked and answered aloud, the researcher was to review the measurement scale within each question, for example:

Think of a 2-dimensional door and consider carefully the image in your mind's eye. How vivid is this image from one to five, with one being no image and five being as vivid as real life?

This allowed the removal of any physical prompts with the scale on, without relying on the participant memorising the scale.

There were many subtopics listed under Dv and Pv together which have been combined under the heading of mental imagery control. The abilities of spatial, object and rotational mental imagery, and the processes of combination, generation and transformation can all, theoretically, be measured according to the same framework of questions. Participants were asked the vividness of an image of an object, then to manipulate this image in a set form and rate the vividness of the new image, before being asked how difficult this manipulation was. Again, the VVIQ question format and rating scale was used for the first two parts, with a one to five difficulty scale being used for the third part of each group of questions. The manipulations are as follows: generation, inspection, scanning, transforming, and rotation. Again, questions were asked and answered aloud, with participants being reminded of the different measurement scales within each question. An example of a group of questions is as follows:

Question 2a: Think of a lamp and consider carefully the image in your mind's eye. How vivid is this image from one to five, with one being no image and five being as vivid as real life?

Question 2b: Think of your lamp and inspect the lightbulb element of your lamp in your mind's eye. How vivid is this new image from one to five, with one being no image and five being as vivid as real life?

Question 2c: How difficult was it to inspect this image from one to five, with one being very difficult, and five being very easy?

The subtopics grouped under Pv should be questioned in two separate sections: intentionality of mental imagery, and memory and imagination. Intention of mental imagery experience refers to a participant's ability to experience mental imagery voluntarily or involuntarily. It further covers their awareness of the experience in design and during a design project itself, and their intentionality in that setting. The intentionality questions were asked directly and answered with 'yes', 'no', or 'unsure' responses as below:

Are you aware of experiencing voluntary mental imagery while you are working on a design project – yes, no, or unsure?

The experiences of memory and imagination imagery are more difficult to measure. While both subjective, memory is straightforward to understand through a shared definition, but imagination less so. Imagination is intricately linked with concepts such as creativity, making it challenging to ask a one-size-fits-all question to every participant that is going to be understood in the same way by all. For the purpose of this study, therefore, it is assumed that participants are following the dictionary definition of imagination: “the act or power of forming a mental image of something not present to the senses or never before wholly perceived in reality; a creation of the mind” (Merriam-Webster.com 2025). The participants were asked to rate their memory and imagination on a scale of one to five, with one being no memory or imagination, and five being photographic memory or very intense imagination. They were then asked to think of a memory, or imagine a new product, and given as much time as needed to generate the image in their mind. Once they acknowledge that they were ready to continue, they were asked how vivid this image is on the VVIQ one to five vividness scale, then how difficult it was to visualise the image on the one to five difficulty scale.

8.2.4 Design task

As the study is attempting to measure the mental imagery experiences of engineering design students while they are designing, it was determined that a design task using protocol analysis would be a reliable form of measurement. Since mental imagery and cognition are subjective, it is challenging to fully understand what a person is experiencing in their mind while they are designing. Recording their cognitive and physical actions while they are working through a design problem is one solution. Participants were asked to complete a design task using a specified, short, design process that was adapted from design methodologies, such as the Double Diamond (Design Council 2025) and Pugh’s Total Design (Pugh 1991). The shortened design process consisted of four design stages: brainstorming (or design thinking), concept generation, concept evaluation, and concept development. Commonly, design cognition research has been undertaken with a primary focus on the early, or concept generation stages of the design process (Dahl, Chattopadhyay and Gorn 2001; Tedjosaputro *et al.* 2014), and on mental imagery’s interaction with techniques often seen during the concept generation stage, such as sketching and mind-mapping (Goldschmidt 1994; 2007; Tedjosaputro *et al.* 2014; 2018). It was determined during the literature review in Chapter 2 that less is known about mental imagery within the design process, and how imagery

changes or adapts throughout. The aim of this study is to define mental imagery in engineering design as a whole experience, rather than on the specific area of concept generation, therefore, it is justified to have students undertaken a design task as a condensed whole design process, rather than a single area.

The total time allocated for the design task was 30 minutes, with participants advised to take five, ten, five, and ten minutes respectively. While the stages were timed, participants were allowed to overrun the time if they were mid-thought when the timer came to an end, which they were advised would be allowed prior to starting the session. The guide given to the participants was scripted and kept open as the aim was to allow them to work in their own way, using their own methods. While they were not being measured on output of design work or concept, such as on quantity of sketches or creativity of final design, they were advised to end with one final design concept to ensure a more consistent manner of working amongst participants.

The design brief selected for the task was taken from a pre-established list of design briefs for good experimental results in design cognition research, as can be found in Hay *et al.* 2019 and Campbell *et al.* 2024. The specific brief was selected through the criteria of it needing to be something recognisable to most participants. The participants were not to be measured on their creativity or originality, but on how they work, so selecting a brief that was easier to understand meant they can focus more on how they work. The final brief is detailed below, and students were given minimal prompts, with the main one being that the focus of the study is on *how* they work:

Sitting in the same position for long periods may be harmful to health. Through your own design process, generate concepts for products that may facilitate physical exercise whilst completing activities in a seated position in the home and office, before selecting and developing a final concept.

The think-aloud method for designing is a verified method for use in design cognition research. It allows researchers to interpret a designer's cognitive actions (Hay *et al.* 2017), and to view their mental process through verbalisations (Lawrie, Hay and Wodehouse 2022). The think-aloud method encourages participants to discuss their thoughts while they are designing, either during the task itself or in a post-task interview (Gero and McNeill 1998; Suwa, Purcell and Gero 1998; Hay *et al.* 2017; Palmiero and Piccardi 2020). Palmiero and Piccardi (2020)

found that visual creativity is heavily influenced by mental representations, and that cognition is a fluid activity, making the think-aloud method a good choice for understanding cognition as it encourages participants to be aware of their design thinking and to verbalise it. There should be minimal interaction with the researcher during the think-aloud method, with interaction limited to, for example, reminders to the participants to keep talking if they are silent for too long (Palmiero and Piccardi 2020). All participants were presumed to have not used the think-aloud method prior to the study, and so a short practice session with an easy design brief was undertaken to get them used to designing while thinking aloud, as proposed by Palmiero and Piccardi (2020). Once the participants were comfortable with the method, they were presented with the full design brief. Participants were provided with the same range of design tools, such as paper, pens, coloured pencils, and post it notes. They were advised that they can use any design tools from the range provided, and any methods they choose provided they use the think-aloud alongside. No further advice was given on how the design process should be conducted.

8.2.5 Interviews

Interview segments allowed for the confirmation of assumptions about the designers' behaviour. Initially one interview session at the end of the design task was planned. However, research highlights that autobiographical memory can be unreliable (Cui *et al.* 2007) and so interviews were included at the end of each design session stage instead to ensure clearer recall of the participants actions and thoughts during the design process. The interviews included set questions to ensure a definitive response to certain topics, such as mental imagery vividness and awareness during the task, but mostly consisted of questions noted during the design session as needing clarification on working methods or mental imagery experiences. The risk of asking leading questions was considered and avoided. Following the design task and interviews, the participants answered a second, short questionnaire that is focused on their mental imagery experience during the design task itself. The questions aimed to quantify specific imagery experiences that occurred during the design task, such as the use of memory and imagination imagery, or their general imagery vividness during the design session.

8.2.6 Coding

Protocol analysis studies usually involve data that needs to be coded as per pre-determined coding schemes, as discussed in Chapter 2. Coding schemes allow the wealth of unstructured data gathered during protocol analysis studies to be organised in a coherent way (Gero and McNeill 1998). The verbal and visual recordings are transcribed, segmented and timestamped before being coded (Gero and McNeill 1998; Suwa, Purcell and Gero 1998), which was undertaken here using Microsoft Excel as a personal preference of the researcher. As per Bilda, Gero and Purcell (2006), the verbal data was segmented first, then segmented again according to the action data. The data was coded twice to ensure assumptions were correct according to the interviews and understanding of mental imagery experiences and was undertaken by the entire set of participants being coded once, then coding was started again to reduce any coder bias that may come with repeated use of the coding schemes respective to participant order. Only one coder was employed due to an increased understanding of the coding, topic and participant sessions, and was justified by the requirement for there to be a strong understanding of the experience of mental imagery, which was developed throughout the research in this thesis. There were minimal changes throughout the second round of coding, but where changes occurred these were accounted for by an improved understanding of the coding scheme. 10% of the coded data was checked by a third party who was determined to have adequate knowledge of the research field. This third party was provided with the coded data and asked to compare with the transcripts, coding scheme and their understanding of the research field. There was over a 90% agreement rate, which was increased to over 96% following deliberation. This confirmed the codes and assumptions were correct, and any failure to agree was deemed accepted by a lower understanding of mental imagery by the third party. Once coding was complete, the data was analysed and mapped. These results were then compiled with the qualitative interpretations of the participants' actions and verbalisations to map out their individual experience of mental imagery during the entire design process.

Protocol data can be coded according to available, pre-existing coding schemes, or a scheme can be developed specifically for the study in question (Tedjosaputro and Shih 2019; Cindioglu, Gursel and Surer 2022). For this research, pre-existing coding schemes from Suwa, Purcell and Gero (1998) and Bilda, Gero and Purcell (2006) have been adapted to create new coding schemes that are study specific and answer the aims of the research. Bilda, Gero and Purcell (2006) used both imagery and sketching coding schemes. Given the importance of both

mental imagery experience and design action to this study, both imagery and action coding schemes were developed and used. The imagery coding scheme will account for interpretations of verbalised thoughts and actions regarding mental imagery experience, while the action coding scheme will cover all physical and cognitive actions, both related and unrelated to the verbalised thoughts. The categories have been named with IDs as per the action scheme presented by Suwa, Purcell and Gero (1998) and adapted for the imagery coding scheme. Further, indices were allocated according to new, continual and revised actions or thoughts, and all data will be coded itself, and by any codes it is “dependent on” (Suwa, Purcell and Gero 1998). Adaptations have been made to include codes that the data is “linked to” and subcategories for more detailed coding and analysis.

The coding scheme presented in Bilda, Gero and Purcell (2006) has been adapted using the FMIR presented in Chapter 6 (Macfie, Hay and Rodgers 2023). Bilda, Gero and Purcell (2006) presented a coding scheme for imagery that included the category of visuospatial action, with inspiration from Kosslyn (1980). This category included elements of imagery generation, inspection, scanning and transforming. While there were other categories in the coding scheme presented, these were deemed less relevant for the current study. The scheme was adapted for this investigation as per the FMIR to create a study-specific coding scheme (Figure 8.1) that includes elements of dimensions of imagery ability (Dx), imagery processes (Px), and the overlap of the two. For Dx, vividness (DV) has been included with subcategories of visual (DVv), movement (DVm) and emotion (DVe) imagery. The visuospatial category has been expanded to cover the entire interconnection of Dx and Px and now includes generation (VG), inspection (VI), scanning (VS), transforming (VT), rotating (VR), spatial (VP), form (VF), and fixation (VX). Finally, the Px category features intentionality (PP), memory (PM) and imagination (PI).

The action coding scheme, Figure 8.2, takes inspiration from Suwa, Purcell and Gero (1998) and Bilda, Gero and Purcell (2006). Bilda, Gero and Purcell (2006) created a sketching coding scheme similar to that in Suwa, Purcell and Gero (1998): Bilda, Gero and Purcell’s (2006) featured perceptual, function, conceptual, evaluative and recall action categories, while Suwa, Purcell and Gero (1998) included cognition as physical, perceptual, function and conceptual actions. For the current action coding scheme, the categories are made up of physical, perceptual, functional and conceptual actions, with physical referring to physical actions, and the other three encompassing cognitive actions. The categories and subcategories

were largely developed from known information and the pilot studies. Additions made to the coding scheme from literature sources are the inclusion of hand gestures (Brown, Chu and Rani 2021) and non-perceptual cognition (NPC) (Lee and Ostwald 2024). Brown, Chu and Rani (2021) found that using hand gestures alongside speech provides a relatively good idea of an individual's mental imagery as gestures convey information themselves. Further, NPC is used to limit external stimuli and distractions which can enhance mental processing (Lee and Ostwald 2024) and is relevant to this investigation of mental imagery experiences.

Category	Description	Category name	Index (n, c, r)	ID	Description	Name
Dimension	Vividness	DV-imagery	new	DVn	Visual	DVv
			continual	DVc	Movement	DVm
			revised	DVr	Emotion	DVe
Visiospatial	Generation	VG-imagery	new	VGn		
			continual	VGc		
			revised	VGr		
	Inspection	VI-imagery	new	VI n		
			continual	VI c		
			revised	VI r		
	Scanning	VS-imagery	new	VS n		
			continual	VS c		
			revised	VS r		
	Transforming	VT-imagery	new	VT n		
			continual	VT c		
			revised	VT r		
	Rotating	VR-imagery	new	VR n		
			continual	VR c		
			revised	VR r		
Processing	Spatial	VP-imagery	new	VS n		
			continual	VS c		
			revised	VS r		
	Form	VF-imagery	new	VF n		
			continual	VF c		
			revised	VF r		
	Fixating	VX-imagery	new	VX n		
			continual	VX c		
			revised	VX r		
	Intentionality	PP-imagery	new	PP n		
			continual	PP c		
			revised	PP r		
Processing	Memory	PM-imagery	new	PM n		
			continual	PM c		
			revised	PM r		
Processing	Imagination	PI-imagery	new	PI n		
			continual	PI c		
			revised	PI r		

Figure 8.1: Imagery coding scheme

Category	Description	Examples	Category name	Index (n, c, r)	ID	Description	Name
Physical	Make depictions	On paper	D-action	new	Dn	Annotations	Da
				continual	Dc	Sketching	Ds
				revised	Dr	With ruler	Dr
						Brainstorming	Db
	Look at depictions	-	L-action	new	Ln	Look at previous depictions	Lp
				continual	Lc		
				revised	Lr	Look at brief	Lb
	Hand gestures	Descriptive	H-action	new	Hn	Design description	Hd
				continual	Hc	Design feature	Hf
				revised	Hr	Previous depiction	Hp
	Other physical actions	Move tools, move design outputs	M-action	new	Mn		
				continual	Mc	Prepare to sketch	Mp
				revised	Mr		
	Non-perceptual cognition (NPC)	Closing eyes, looking away, averting gaze	N-action	new	Nn	Closes eyes	Ne
				continual	Nc		
				revised	Nr	Looks away	Na
	Silence	-	X-action	new	Xn		
				continual	Xc		
				revised	Xr		
Perceptual	Attend to visual features (form)	Of concepts; shapes, sizes, textures	P-action	new	Pn		
				continual	Pc		
				revised	Pr		
	Organise or compare elements	Between or within concepts	O-action	new	On		
				continual	Oc		
				revised	Or		
	Make assumptions	About brief, requirements	A-action	new	An		
				continual	Ac		
				revised	Ar		
	Attend to spatial relations	Of concepts, features or brief	C-action	new	Cn		
				continual	Cc		
				revised	Cr		
Functional	Resolve conflicts	-	R-action	new	Rn		
				continual	Rc		
				revised	Rr		
	Functions	Adding, changing or removing	F-action	new	Fn		
				continual	Fc		
				revised	Fr		
	User interactions	-	U-action	new	Un		
				continual	Uc		
				revised	Ur		
	Design process	Working, methods or tools	W-action	new	Wn	Difference	Wd
				continual	Wc		
				revised	Wr	Sketching	Ws
	Make decisions	About concepts, features	V-action	new	Vn		
				continual	Vc		
				revised	Vr		
	Aesthetics and preferential evaluations	Like, dislike	E-action	new	En		
				continual	Ec		
				revised	Er		
	Goals	Brief, requirements	G-action	new	Gn		
				continual	Gc		
				revised	Gr		
Conceptual	Knowledge	Memory	K-action	new	Kn		
				continual	Kc		
				revised	Kr		
	Discuss issues	With concepts	I-action	new	In	Design	Id
				continual	Ic		
				revised	Ir		
	Solutions	Generating	S-action	new	Sn		
				continual	Sc		
				revised	Sr		

Figure 8.2: Action coding scheme

8.3 Study pilot

8.3.1 Methodology

The aim of the pilot was to trial different elements of the full study and make changes where intended outcomes were not achieved. The length, detail, and wording of the script was piloted to ensure that it gave enough detail to the participants without being leading or adding unintended variables. For the questionnaire, the questions, order, measurement form and method of asking and answering were tested. The design task was investigated with questions on the length and set up, as well as the design brief itself. It was initially planned as a set of mini design tasks from a selection of briefs, and this needed to be trialled, along with alternative set up options. Further, as the think-aloud method is a new design method for the researcher and, presumably, most of the study participants, the practice and explanation of the method should be piloted to ensure the participants understand what is being asked of them. Additionally, the design process being measured and worked through was piloted to ensure best practice. Finally, the interview portion of the investigation was piloted to confirm when it will take place, how it will work, and what will be asked.

Third year PDE, PDI and SDE students were utilised for the pilot study and participation was on a voluntary basis. Third year students were used as they would have an appropriate understanding of the design process, having undertaken classes in engineering design and development throughout their three years of study. No information was recorded of the participants, except their course information. All participants were required to sign a consent form acknowledging the use of the information gathered in research writing, and that they would be audio and video recorded.

Pilot sessions one to four enabled the trial of different components of the design task, and pilot sessions five to seven were to trial the full investigation, albeit with a shorter design session. All sessions were both audio and video recorded, both to assist with making any changes to the equipment and study details, and to help with creating the coding schemes and practice of coding the data. The room used was the same as the full study, and it was set up in the same manner, with the exception of the pilot where the participant was to be standing for the design task. The equipment and tools were trialled within the pilots to ensure a lack of variables and rigorous study methods.

8.3.2 Pilot sessions

Pilot 1

The first pilot session had the aim of conducting an initial trial of the think-aloud method. The think-aloud portion of a design task that focused solely on concept generation was performed following a demonstration of the method then a practice session for the participant. This used the design prompt “wooden toy for children” and featured the researcher demonstrating to the participant the think-aloud method in practice. The following practice task used the design prompt “design a bookshelf that is more than just a bookshelf”. The participant was then presented with a short, verbal design brief and tasked with generating concepts, while the researcher took notes throughout before following up with interview questions. The design task was as follows:

Design a product for drying clothes outside in a garden or on a balcony.

The demonstration of the think-aloud method was removed as it was found to be too leading as, whether unintentionally or not, it encouraged the participants to complete the task in the same way they had seen the researcher. Additionally, the script was too detailed in parts resulting in it being too leading. More emphasis also needs to be provided on the rule that they can work however they see best with whichever methods they choose. The mini tasks were ruled out at this point as the short time unnecessarily restricts the design process. The design task prompted numerous questions from the participant, which could be a personal issue, or may reflect a wider issue with the design brief so it should be trialled again.

Pilot 2

The aim of the second pilot study was to trial a new version of the script and the removal of the demonstration from the design task portion of the study. Again, the focus of the pilot was on the think-aloud method and concept generation, a better explanation of which was scripted and given to the participant. The practice session and main design task prompts were the same as in pilot one, and interview questions were given in the same manner, covering both imagery experience and feedback of the session. The script was found to still be too leading at parts, with too much emphasis given on the methods they could use and not enough emphasis on the flexibility of the task. It was noted that the participant was quiet during brainstorming and a method for encouraging talking without interfering should be found before the main study. For the main study, notes should be taken on what questions to ask

during the interview. The same issues with the design brief were noted and so changes need to be made, including for the brief to be written out in full and presented to the participant for them to easily refer back to.

Pilot 3

The third pilot session aimed to trial a longer design task time to ensure this did lead to a better outcome and allowed the participant to harness more of their design process. The script was more detailed, and the think aloud method was performed over half an hour, rather than ten minutes. The practice session and main design task were the same as previous pilots, and the interview manner was the same. The participant noted that the think-aloud method is difficult, so it may be that a more detailed practice session is needed, although this will be dependent on time constraints. They also noted that it was hard not having feedback from the researcher to their verbalisations. Since the researcher needs to not impact on the session at all, they will sit further away from the design space in future sessions, so as to not interfere, unintentionally or not. The aim of this pilot was to test the longer time for the design task, and this worked well, although for the full design sessions, this should be split into different design process steps to ensure the participants are covering all necessary design stages.

Pilot 4

The aim of pilot session four was to trial the think-aloud design task with the participant designing while standing up to confirm if it was easier or more difficult for them to talk their thoughts aloud while standing. For this pilot, the participant was given five minutes for thinking about the task, then ten minutes for concept generation. The practice and design briefs were the same, as was the interview question arrangement. The results of pilot session four showed that while standing encouraged the participant to talk more directly, it did not make it any easier for them to explain their thoughts while designing. It encouraged too much communication with the researcher by creating a presentation-type scenario.

Pilot 5

As mentioned, pilot studies five to seven contained more components of the study than only the design session. The aim of these pilots was to trial as much of the full session as feasible, while still being aware of voluntary time. For pilot session five, the questionnaire was presented with the questions in a continual, follow-on order, where questions were grouped according to design elements in common. The participant was asked to complete the design

task with the full range of tools available to them and again were asked only to undertake concept generation. The practice session brief remained the same, but the participant was presented with four trial design briefs to choose from, as seen in Appendix 14. They were advised to choose whichever brief they were least familiar with or had least experience with, and participant five chose:

Design a product for storing personal items in a small bathroom.

Finally, the interview portion of the pilot study featured interview questions in the same manner as the previous pilots.

During pilot session five it became clear that the interview needs to be split into sessions that occur after each stage of the design process, and that the participants will benefit from 30 minutes design time, rather than the ten minutes given. This will allow them to think more in depth about the design brief and come up with a more developed solution. While the participant reported that they found the design-based questions in part one of the questionnaire made sense, they felt some of the questions were too similar and so it would be beneficial to clarify or change some elements. One example of this is that the wire coat hanger in question eight is very similar, or triggered similar visuals in the participant's mind, as the 2D door in question one, due to the physical shape and depth of a wire coat hanger. Further, the participant said they would have benefitted from the questions being more random so that there was no continuation of theme. For example, going from the 2D door in question one to the 3D shed in question two was easy when they were already visualising the door, and they felt they may have understood their imagery vividness better if there was no pre-generated image. Mixing up the order of the questions will be trialled in pilot six, with the standard order trialled again in pilot seven to check the validity of the change.

Pilot 6

Again, pilot session six was used to trial the full study session, but with a different design brief. The questionnaire was presented but following the results of pilot session five, the questions in part one were rearranged to a random order so that there were no continuity elements. For the design session, the participant was presented with three design briefs, removing the one selected by participant five to trial more of the options. Again, they were given ten minutes for concept generation, and selected:

Design a product for eating meals as a family in a small apartment.

The interview, again, was only one section due to the shorter design session, and the repeat questionnaire remained the same as pilot study five.

As per the previous pilot session, the time constraint for the design session was difficult for the participant to navigate and confirms that for the full study, the longer duration of time will be required. Unfortunately, there were audio recording issues during this pilot study, which will need to be rectified prior to the full study beginning. It was apparent during all questions that there is a need to read the full question and answer options to the participant for every question, for example if the participant is to answer a question with “yes”, “no”, or “unsure”, this should be stated. One noted issue for the participant is that they stated that their thoughts move too fast in their own head compared to their physical abilities, making the think-aloud method difficult.

Pilot 7

The final pilot trialled the full study again with another new design brief. Part one of the questionnaire returned to the original order of the questions: while pilot session six found that the random order worked well, clarifying it by re-trialling the original order is a necessary step to ensuring the best outcome. Participant seven was presented with only the remaining two design briefs and selected:

Design a workspace or product for working from home in a shared space in an apartment.

The interview process and repeat questionnaire remained the same, as did the timings for the design session.

There were many components of pilot session seven that required attention and possible redesign. Firstly, the participant was talking to the researcher a lot throughout the design session, which appears to be an issue with certain personality types and can be rectified by the researcher moving further from the design space. There also needs to be a clear method for prompting participants to keep talking throughout their design session. Additionally, the briefs should be changed to use a more trusted and well-structured set brief for all participants as the ones provided during the pilot sessions returned some uncertainty in the participants. As for the participant themselves, they reported that certain questions, for example the set of dinner plates in question 13, had a lot of variables in how the question could be interpreted. The solution for this is to clarify exactly what is to be visualised in the question, with the only room for interpretation being the participant’s visual itself. Finally, the participant stated that

they did not notice any pattern with part one of the questionnaire so continuing to mix up the order removes any risk of impact from previous imagery.

8.4 Limitations of the study

The preliminary studies undertaken were overall a positive experience with the necessary steps taken to eradicate any foreseen variables. There were variables and limitations during the final study that had not been considered and that have been noted during the analysis stage. While the set up for the investigation was in an appropriate space, the only proposed change would be an external camera to avoid any distraction for the participant, although this issue seems to have been negligible based on the recordings of each session. While the researcher attempted to mitigate feedback issues by reading the questions during part one aloud to participants, this created a potential variable in speed and understanding so a different method may be beneficial in future. Additionally, more structured reminders to keep talking would have been useful. It should also be noted that while the design brief was a good choice that led to a good depth of design process work, it is possible that there would be different outcomes if this investigation was repeated with a different brief, students at different stages of study, or if there were different risks and rewards associated. One example being if this study was undertaken as part of a design module with a graded element, it can be expected that participation levels would change. Another example being that first-year students would likely act differently than the fourth- and fifth-year students that participated in this study.

When it came to coding the data, each stage of every session was coded in depth with action and imagery codes, as well as being timestamped. During the analysis of the data, it was discovered that the data was largely over-coded. The questionnaires and interviews did not need to be coded in full, with the questionnaire analysed independently to interpret the designers' understanding of their own mental imagery, and for how successful the questions were in measuring the mental imagery experience, while the interviews were used to confirm the assumptions about the designer's work and intentions during the design session. The experience of over-coding the data did allow for a better understanding of the participant's actions and experiences, however, with a much more in-depth view of the design process being uncovered through this work. One area of concern was that the think-aloud method may overlook what is happening in a designers' mind when they are not talking their thoughts aloud, but there are restrictions on how to navigate this issue. It is possible that objective

methods such as eye-tracking could be utilised in future research, but it is not certain if this would have the necessary results and was outside of the scope of this investigation. Positively, most of the codes utilised during the study were developed prior to the coding work beginning, with the only exceptions the addition of subcodes Ds (depiction-sketching), Da (depiction-annotations), Lb (looks at brief), Lp (looks at previous depictions) and Mp (prepares to sketch).

8.5 Part One (questionnaire) results and analysis

The questionnaire in part one of the study was a useful inclusion for deciphering what would work in a design-focused mental imagery questionnaire. While it did not provide definitive results on each participant's mental imagery experience, it did help to understand the participants' thinking and the type of questions that will assist in producing similar answers without a full-scale study. There was not a definitively correct method between listening and reading, and so it would be more prudent for a questionnaire to be in reading format as has been validated by previous research, such as the VVIQ (Marks 1973). A written and read questionnaire is simpler to understand, contains no risk of variables, and is easier to distribute to a larger number of participants. Lastly to note is that a future questionnaire should be able to adapt to how the participant responds to a question to ensure it accounts for varying mental imagery experiences, for example asking different questions if a person reports aphantasia than if they report hyperphantasia.

Part one of the questionnaire asked participants to rate the vividness of scenarios that highlighted different design elements, and part three asked similar questions but highlighting different control elements of mental imagery. When comparing the responses to these questions with the VVIQ results of participants, the results are largely similar across the three sets, as can be seen in Figure 8.3 There are two outliers in participant two (P-2) and P-5, where both perform better on the design focused questions, as can be seen in Table 8.1. The outcome of this analysis is that including different elements or design scenarios in a questionnaire appears to have no negative impact, and in most situations generates more positive results. The main question that this part of the research leads to is whether there is a better method of incorporating design elements into the questionnaire, potentially through a more design-scenario led focus.

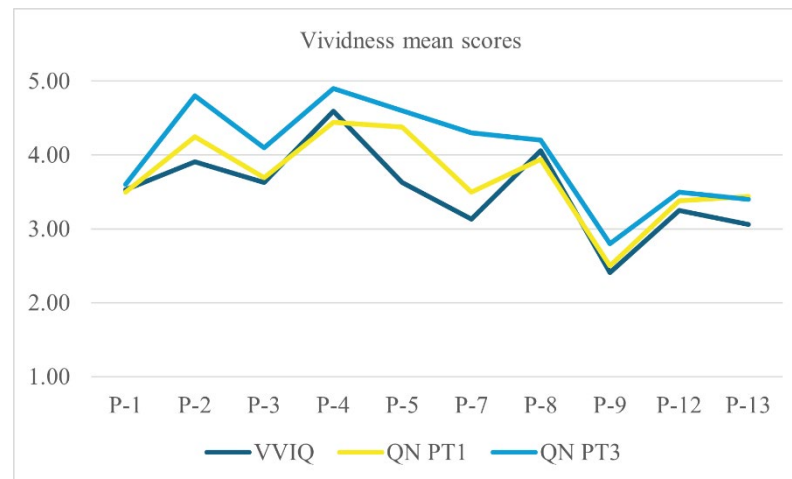


Figure 8.3: Overall mean responses per participant to varying vividness question sets

Participant	VVIQ	QN PT1	QN PT3
1	3.53	3.50	3.60
2	3.91	4.25	4.80
3	3.63	3.69	4.10
4	4.59	4.44	4.90
5	3.63	4.38	4.60
7	3.13	3.50	4.30
8	4.06	3.94	4.20
9	2.41	2.50	2.80
12	3.25	3.38	3.50
13	3.06	3.44	3.40
Mean	3.52	3.70	4.02

Table 8.1: Overall mean responses per participant to varying vividness question sets

Part two of the questionnaire asked participants about their intention, with the design focused questions being followed up immediately after the design session finished. As can be seen in Figure 8.4 there are clear differences in how participants responded before and after the design session. There were significantly more “yes” responses and less “no” or “unsure” responses after the design session, with 22 “yes”, three “no” and five “unsure” before versus 28 “yes” and one each of “no” and “unsure” after. This indicates that participants have a better understanding when discussing their experience after a design session when their process is more recent in their minds. This highlights the potential of incorporating a design focus in a questionnaire: it would be beneficial for participants to undertake a design activity in some manner but without a full hour-long process. One potential method would be to include only concept generation, by having participants generate a concept to a brief.

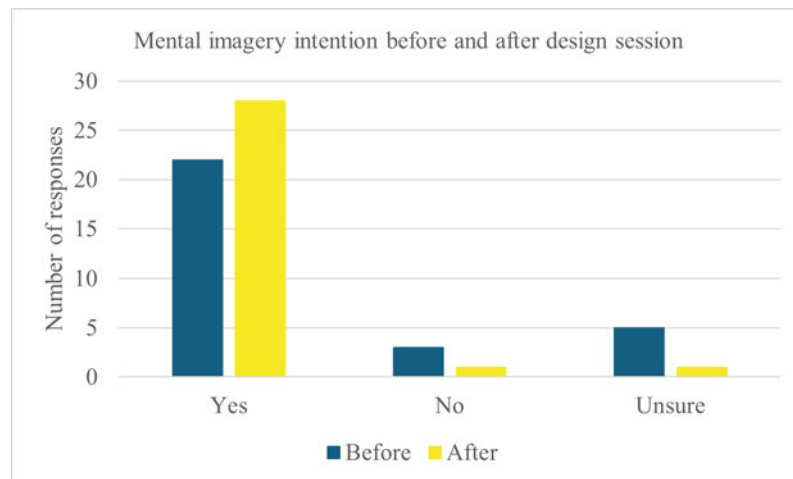


Figure 8.4: Responses to three mental imagery intention questions before and after design session

In part three of the questionnaire participants were asked how difficult it is to control their mental imagery, alongside the vividness questions (seen in Figure 8.3). While the difficulty of mental imagery is challenging to analyse, it is interesting to understand their experience with respect to any decisions they make within their own mind. There is no true correlation seen between difficulty and vividness of mental imagery, but it is useful to see what differences occur between participants, with the difficulty shown in Figure 8.5. This understanding would be beneficial in design situations to know how an individual works and adapts, for example it would be helpful in educational settings to understand how a student's cognitive diversity impacts on their learning style.

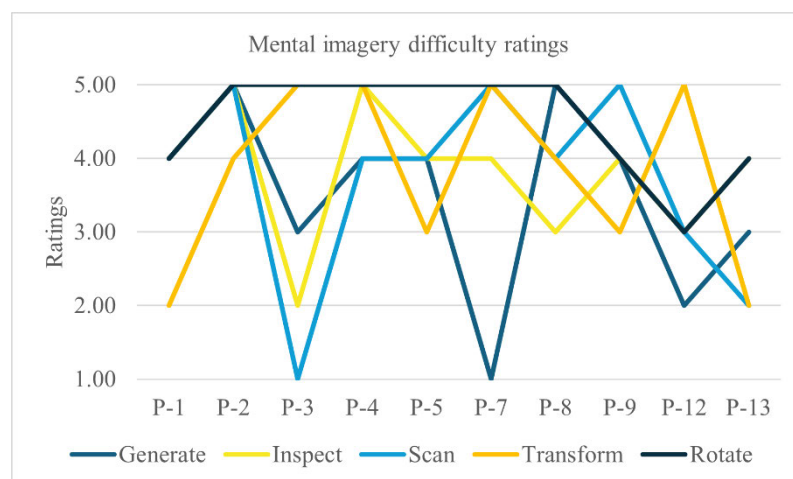


Figure 8.5: Overall mean responses for difficulty of mental imagery control

Finally, participants were asked questions on their experience of memory and imagination imagery. There were higher ratings overall for imagination, as seen in Figure 8.6 but imagination is a highly subjective topic making it difficult to truly judge in a situation. Of interest is that both vividness and difficulty responses were higher for memory (meaning that participants reported higher memory vividness and easier generation of memory), despite the reports that they feel their imagination is “stronger”. The results can be seen in Figure 8.8 and again raise the question about how much of an impact personal interpretation has on the measurement of memory and imagination imagery. To include this research in a questionnaire, it may be necessary to find a way to judge imagination objectively, or rely on subjective reports of ratings, rather than forcing the generation of imagination onto a participant, as was asked here.

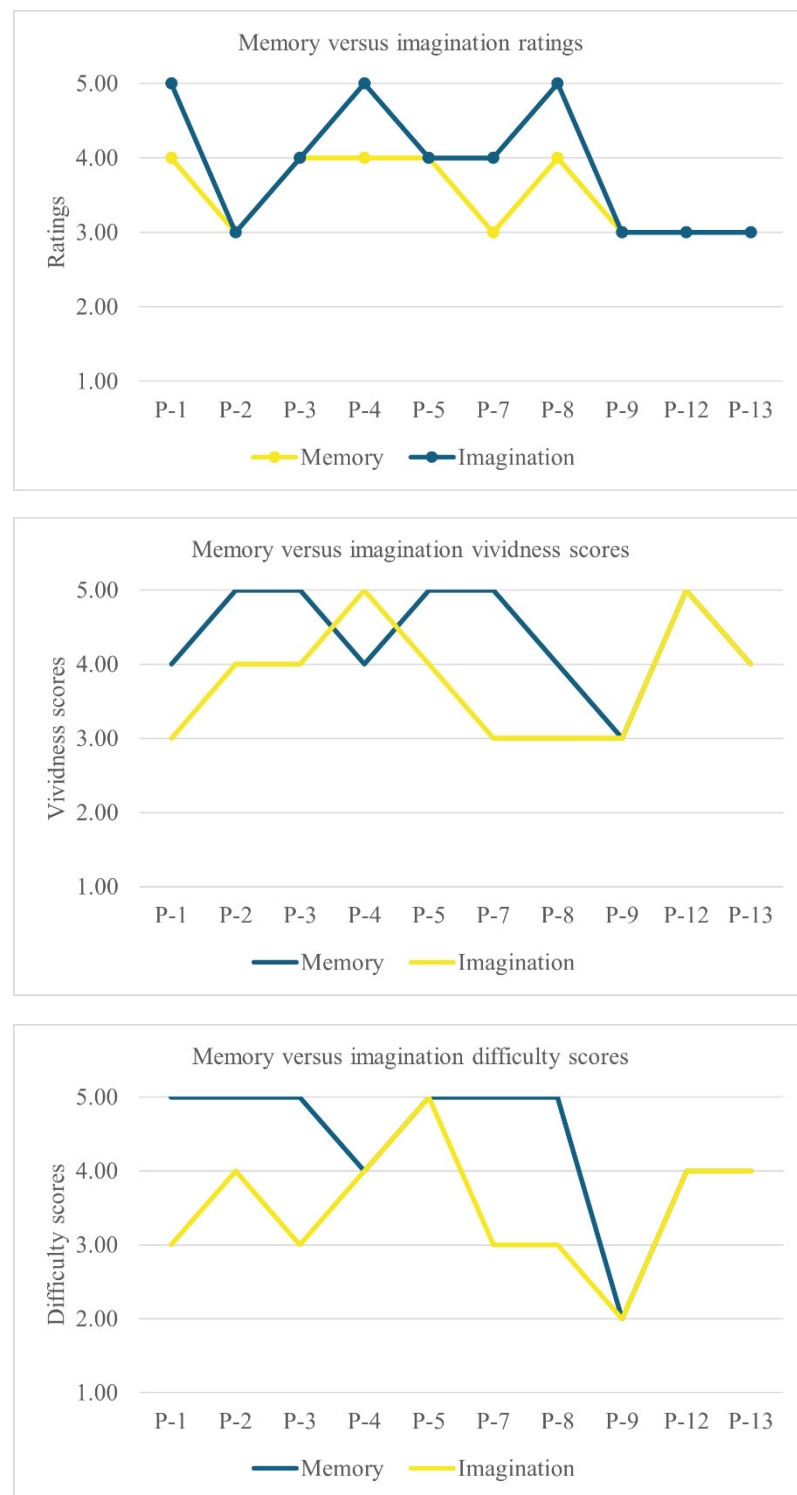


Figure 8.6: Overall rating, mean vividness, and mean difficulty responses for memory versus imagination

8.6 Coding occurrence and link data

Thirteen participants took part in the study, with three removed at the analysis stage for varying technology-related issues that impacted the quality and availability of the camera recordings. While work was undertaken to attempt to resolve these issues, it was decided that due to the time-restricted nature of the project and both the quantity and quality of the remaining data, it would be justified to continue with the ten participants that required no further attention. As the researcher was in attendance throughout each entire design session and was witness to the design processes of the participants, it was clear that there was rich data collected prior to analysis. Of the remaining ten participants, all were on Masters-level courses, with six out of ten in their fourth of five years of study, and four of ten in their fifth and final year of study. Four out of ten participants were on the PDI course, five out of ten on the PDE course, and only one of the ten was on the SDE course. The participants were all required to undertake the VVIQ prior to their session to ensure they all do experience visual imagery. Five out of ten participants reported an overall high level of vividness of visual imagery, three of the participants reported overall moderate levels of visual imagery vividness, and one each reported potentially hyperphantasic imagery and low imagery vividness.

8.6.1 Participant 1

Occurrence

Over their entire design process, there were 121 logged imagery codes alongside 496 action codes. P-1's design process was categorised into 316 segments over a total time of 25 minutes and nine seconds. This calculates to an average of 4.80 seconds spent on any one segment across the entire design process. 121 of the total segments logged imagery codes at 38%, with zero of these being imagery-only codes: all imagery codes had at least one concurrent action code. Of the total segments, 313 (99%) logged action codes with 192 (61%) of these being action-only codes. Only three segments were left uncoded at 1%. There were an average of 0.38 imagery codes and 1.57 action codes for any one segment.

P-1's total brainstorming (BRS) time was seven minutes and one second, with 94 total segments catalogued, 40 imagery codes total, and 153 action codes. The average time spent on each segment was approximately 4.50 seconds. 40 of the segments were assigned imagery codes which accounts for 42.50% of the total segments, while all 100% of segments were

assigned at least one action code. There were no segments coded with imagery only, while all imagery-coded segments were also action-coded, and there were zero uncoded segments. 57.50% of all coded segments were assigned action codes alone, and there were an average of 0.43 imagery codes and 1.63 action codes for each segment. For P-1's concept generation (GEN) portion of the design task, they logged a total of 37 imagery codes and 135 action codes across the 80 total segments. At a total time of seven minutes and two seconds, each segment averaged at 5.30 seconds in length. 46% of the segments were recorded as imagery coded, with concurrent action codes logged against all segments and no segments containing only imagery codes. All 80 segments were action coded, with 43 of these coded as only action, and there were no uncoded segments. The average number of imagery and action codes per segment were 0.46 and 1.69 codes respectively. During concept evaluation (EVA), P-1's process recorded 18 imagery codes and 85 action codes against 54 segments and over four minutes and 11 seconds. The average time per segment was 4.70 seconds. All 18 of the imagery codes covered 33.33% of the segments, with no segments logged as imagery only. 85 action codes were logged against the 54 segments, with no uncoded segments, 66.67% of these as action-only segments, and 18 of these 54 action-coded segments were also recorded with imagery codes. There was an average of 0.33 imagery codes per segment, and 1.57 action codes. Finally, P-1's concept development (DEV) was made up of 88 total segments over six minutes and 55 seconds, at an average of 4.70 seconds per segment. There were 26 imagery codes and 123 action codes recorded in total. All 26 of these imagery codes were accounted for by 29.50% of the 88 segments, with no segments recorded as imagery-only, and all 26 imagery codes concurrent with action codes. 97% of segments featured action codes at a total of 85, with three segments (3%) remaining uncoded. There were an average of 0.30 imagery codes and 1.40 action codes per segment.

The total sum of P-1's imagery codes is 121, with index totals of 69 new (57%), 52 continued (43%), and no revised codes. 4 (3%) of the 121 codes were dimension (Dx) codes, 96 (79%) were visuospatial (Vx) codes, and 21 (18%) were processing (Px) imagery codes. Of the Dx codes, zero were recorded as DV or DVv codes, and three were assigned as DVm codes which accounted for 75% of all Dx codes, and 3% of the total number of imagery codes. Further, one segment was recorded as DVe which made up 25% of the Dx-coded imagery segments, and 0.83% of all segments. The Dx-coded index totals were three new codes (75%) and one continued code (25%). For the Vx subcodes, none of the segments were assigned VI, VS, VR, VF, or VX. 28 were recorded as VG which totalled 29% of all Vx codes, and 23% of

all segments imagery-coded, while 29 segments were coded as VT (30% and 24% respectively), and 39 segments were coded as VP (41% and 32%). 53 of the Vx codes were new (55%), and 43 were continued (45%). Only one Px code was assigned as PP at 5% of all Px codes, and 0.83% of all imagery codes. A further 18 segments were logged as PM codes (86% and 15% respectively), and two as PI (10% and 2%). The index totals for the Px codes were 13 new (62%) and eight continued (38%).

There were 40 total imagery codes recorded for the BRS stage of P-1's design process, with three (7.50%) of these being Dx-codes, 28 (70%) Vx, and nine (22.50%) Px. There were two DVm codes and one DVe code, five VG codes, 11 VT codes, and 12 VP codes, and one PP code, eight PM codes, and zero PI codes. For the GEN portion, there was a sum total of 37 imagery codes recorded of which one of these was a Dx code (3%), 31 a Vx code (84%), and five a Px code (13%). The only Dx code was a DVm code, with no DVe codes. There were 11 VG, nine VT, and 11 VP codes, with zero PP, four PM, and one PI code. During the EVA section, 18 imagery codes were logged, with zero Dx codes for the entire section. Additionally, there were 14 (77%) Vx codes, made up of five VG, two VT and seven VP, and four (23%) Px codes consisting of zero PP, three PM and one PI code. Finally, the sum total of imagery codes logged during DEV for P-1 was 26. Again, none of these were Dx-coded, while 23 were Vx (88%) and three were Px (12%). Of the total Vx codes, seven each were VG and VT, with nine being VP, and of the Px codes, none were PP, three were PM and none were PI.

P-1's action-code total is 496, with a total index of 224 new action codes (45%), 263 continued action codes (53%), and nine revised action codes (2%). Of these, 342 were recorded as physical action (PhA) codes (69%), 64 as perceptual action (PeA) codes (13%), 31 as functional action (FA) codes (6%), and 59 as conceptual action (CA) codes (12%). A total of 154 (31%) of the action codes were assigned as cognitive actions, as opposed to physical. Of the PhA codes, 212 were depiction (D-a) codes at 62% of the total PhA codes, and 43% of all action-coded segments, 67 were looking (L-a) codes (20% and 14% respectively), 14 were hand gesture (H-a) codes (4% and 3%), three were movement (M-a) codes (0.88% and 0.60%), eight were NPC (N-a) codes (2% and 1.50%), and 38 were silence (X-a) codes (11% and 18%).

The PeA codes for P-1 were assigned as ten features (P-a) codes (16% of all PeA codes and 2% of the total action codes), 30 elements (O-a) codes (47% and 6% respectively), two assumption (A-a codes) (3% and 0.40%), and 22 space (C-a) codes (34% and 4%). For the FA codes, there were seven assigned to the function (F-a) category code (23% of all FA

codes and 1% of all action codes), 12 to the user (U-a) category (39% and 2%), one to the decision (V-a) category (3% and 0.20%), and 11 to the working (W-a) category (36% and 2%). Lastly, four of the CA codes were recorded as opinion or aesthetic (E-a) codes (7% of all CA codes and 0.81% of all action codes), 12 as goal (G-a) codes (20% and 2%), eight as knowledge (K-a) codes (14% and 2%), 12 as issue (I-a) codes (20% and 2%), and finally, 23 as solution (S-a) codes (40% and 5%).

Links and networks

“Back” links have been categorised in the study as any imagery links that have been coded “dependent on” a separate imagery code. P-1’s design process logged 25 types of back links overall across all sections. There were 22 VP to VG links, and the full matrix of back links can be found in Table 8.2, with the networks for each design stage found in Appendix 15. The BRS stage returned 19 types of links, GEN 14 types, EVA 11 types, and DEV eight types. Additionally, there was a shared network of links between each stage that included links VG to PM, VT to VG, VP to VG, VP to VT, and PM to VG.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	1	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	1	0	0	1	0	3	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	0	0	0	0	0	11	0	22	0	0	0	10	0
VI	0	0	1	0	0	0	0	0	1	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	3	0	0	0	0	9	0	0	0	2	1
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	2	0	5	0	0	10	0	0	0	0	0	4	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0	0	0	1	0
PM	0	1	0	12	0	0	5	0	4	0	0	1	0	1
PI	0	0	0	6	0	0	2	0	0	0	0	0	1	0

Table 8.2: Back imagery links for P-1

“Other” links covers all links made between imagery codes that were logged under “linked to” whilst coding the segmented data, of which there were 30 types of links total for P-1. These included 14 VG to PI links. The full matrix of other links can be found in Table 8.3, with each design stage network found in Appendix 15. There were 17 types of other links for the BRS stage, 19 for GEN, 12 for EVA, and 11 for DEV. Shared networks were found between VP to VG, VP to VT, VP to PM and PM to VG.

	Imagery codes													
Links	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	1	0	0	1	0	3	0	0	0	1	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	2	1	0	0	0	8	0	7	0	0	0	5	1
VI	0	0	0	1	0	0	0	0	0	0	0	0	1	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	2	0	0	0	0	9	0	0	0	2	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	0	0	2	0	0	3	0	0	0	0	0	1	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	1	0	0	0	0	2	0	0	0	2	0
PM	0	1	0	7	0	0	7	0	11	0	0	0	0	1
PI	0	0	0	14	0	0	9	0	7	0	0	0	5	0

Table 8.3: Other imagery links for P-1

All concurrent imagery and action codes have been logged as imagery-action links and networks. For P-1's overall design process, PhA returned 122 links and 25 types of link and PeA returned 52 links with 14 types of links. There were found to be 19 FA links along nine types of links and there were 40 CA links over 16 types of links, with the entire total design process link matrix for P-1 found in Table 8.4. Additionally, P-1 had a shared network featuring links between VP:C-a, VP:Ds-a, VP:U-a, VG:Ds-a, and PM:Ds-a.

The BRS stage of P-1's design process contained 79 imagery-action links over 37 types of links. PhA links totalled 44 with 16 types, PeA totalled 16 with eight types, FA totalled five with four types, and CA totalled 14 links with nine types. The GEN stage featured 72 links with 29 types of links: 36 of these were PhA action codes with nine types of links, 13 were PeA with eight types, seven were FA with five types, and 16 were CA with seven types. 33 links were found total for the EVA section over 23 types of links. PhA links totalled 18 across 11 types, two PeA with only one type, four FA across three types, and nine CA across eight types. Finally, the DEV section totalled 50 links across 16 types, with 25 of these being PhA (5 types), 21 PeA (eight types), three FA (two types), and only one CA link was found. Each stage network depicting the total links can be found in Appendix 15.

Action	Imagery													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Da	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ds	0	2	0	22	0	0	24	0	25	0	0	1	10	1
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	1	1	4	0	0	2	0	9	0	0	0	3	1
Lp	0	0	0	1	0	0	1	0	3	0	0	0	2	0
Lb	0	0	0	0	0	0	0	0	1	0	0	0	0	0
H	0	0	0	1	0	0	0	0	3	0	0	0	0	0
Hd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	0	0	0	0	0	0	1	0	0	0	0	0	1	0
Hp	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mp	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	0	0	1	0	0	0	0	0	0	0	0	1	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	2	0	0	6	0	1	0	0	0	1	0
O	0	0	0	4	0	0	8	0	5	0	0	0	3	1
A	0	0	0	0	0	0	0	0	0	0	0	0	1	0
C	0	0	0	2	0	0	2	0	15	0	0	0	1	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	0	0	3	0	0	3	0	1	0	0	0	0	0
U	0	1	0	2	0	0	0	0	6	0	0	0	0	0
W	0	0	0	1	0	0	0	0	0	0	0	0	1	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	0	0	0	0	0	0	1	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G	0	1	0	0	0	0	1	0	1	0	0	0	2	0
K	0	0	0	1	0	0	0	0	1	0	0	0	5	0
I	0	1	0	1	0	0	2	0	3	0	0	0	1	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	0	0	10	0	0	6	0	3	0	0	0	1	0

Table 8.4: Concurrent links for P-1

8.6.2 Participant 2

Occurrence

For P-2's entire design process there were 426 segments overall over a combined design time of 28 minutes and 53 seconds. This equates to approximately one segment every 4.07 seconds. Over this period there were 77 logged imagery codes and 698 action codes, with the imagery codes being logged over 18% of the segments. All imagery codes were recorded alongside action codes. There were 422 segments logged with at least one action code, accounting for 99% of all segments: four segments remained uncoded (0.94%). 81% of all coded segments contained only action codes. There were an average of 0.18 imagery codes and 1.64 action codes per segment.

Over the five minutes and 22 seconds design time for P-2 during the BRS stage there were 58 segments categorised, at an average time per segment of 5.55 seconds. During this time there were 20 imagery codes logged and 91 action codes. The 20 imagery codes across 20 segments recorded accounted for 48% of all segments, with all of these having concurrent

action codes. There were 55 action-coded segments total (97%) and three uncoded segments (5%): of the action-coded segments, 60% of these contained only action codes. The BRS stage averaged 0.34 imagery codes and 1.57 action codes per segment. For the GEN stage there were 105 categorised segments over six minutes and 52 seconds. This calculates to 3.92 seconds per segment, with 20 imagery codes and 172 action codes recorded in total. 19% of segments were assigned an imagery code, and all of these had concurrent action codes. 104 segments were coded with at least one action code at a total of 99%, and 80% of segments were action-only coded. There was one uncoded segment (0.95%) and an average of 0.19 imagery and 1.64 action codes assigned to a segment. There were a further 106 segments categorised for the EVA stage of the design process. This was over six minutes and 15 seconds, with an average of 3.54 seconds per segment. There were 12 imagery codes, and 167 action codes assigned total, with 11% of segments receiving imagery codes. 100% of segments were assigned action codes, with all 11% of imagery codes receiving concurrent action codes, and the remaining 89% of segments logged as action-only codes. There were approximately 0.11 imagery codes per segment and 1.58 action codes. Lastly, the DEV stage ran for ten minutes and 24 seconds with 157 logged segments at an average of 3.98 seconds per segment. With 25 imagery codes logged and 268 action codes, all 16% of imagery-coded segments were also coded with action codes. All 157 segments were assigned a minimum of one action code, with 132 of these (84%) being action-only. There were no uncoded segments and an average of 0.16 imagery and 1.71 action codes per segment.

The overall occurrence of imagery codes for P-2's entire design process was a sum of 77, with 63 of these being indexed as new codes (82%), 14 as continued codes (18%) and none as revised codes. There were 12 Dx codes (16%), 53 Vx codes (69%) and 12 Px codes (15%) logged. Only DVm codes were logged from the Dx category with nine of these being new (75%) and three continued (25%). There were no VI, VS, VR or VF codes logged, 29 VG codes (55% of all Vx codes total and 38% of all imagery codes), 11 VT and 11 VP codes (21% and 14% respectively, each), and two VX codes (4% and 3%). 44 of these Vx codes were indexed as new (83%) and nine as continued (17%). Further, there were no PI codes assigned, two PP codes at 17% of all Px codes and 3% of all imagery codes, and ten PM codes (83% and 13% respectively). Ten of the 12 Px codes were new (83%) and two were continued codes (17%).

There was a total of 20 imagery codes recorded during the BRS stage, with three Dx codes (15%), ten Vx codes (50%), and seven Px codes (35%) logged. Only DVm codes were logged under the Dx category and only PM codes under Px, while six VG, one VT and three VP codes were recorded for the Vx category. During the GEN stage, P-2 logged 20 imagery codes, with seven Dx (35%), nine Vx (45%), and four Px (20%). There were again only DVm codes recorded for Dx, as well as only VG codes assigned under the Vx category. Additionally, there were two recorded PP codes and two PM codes. For the EVA stage there were 12 assigned imagery codes with one Dx (8%, recorded as DVm), 11 Vx (92%), and zero Px codes. There were four VG codes assigned, five VT, and two VX. Finally, there were 25 total imagery codes assigned for the DEV stage. One of these was recorded as Dx (4% and DVm), 23 as Vx (92%), and one as Px (4% and PM). Ten of the 23 Vx codes were assigned as VG, five at VT, and eight as VP.

P-2's segmented design process was assigned a total of 698 action codes across all stages of the process. 337 of these were indexed as new codes (48%), 300 as continued (43%), and 61 as revised (9%). There was a total of 541 assigned PhA codes (78%), 45 PeA codes (6%), 44 FA codes (6%), and 68 CA codes (10%). In total, 157 action codes were cognitive actions at 23% of the total 698. Of the 541 PhA codes, 216 were assigned as D-a codes (40% of PhA codes, and 31% of all action codes). Further to this, 157 of the PhA codes were assigned to the L-a category at 29% and 22% respectively, while 30 were recorded as H-a codes (6% and 4%). There were 43 logged M-a codes (8% and 6%), four N-a codes (0.74% and 0.57%), and 91 X-a codes (17% and 13%).

With the 45 PeA actions, two were assigned as P-a (4% of PeA actions and 0.29% of the total actions), 35 as O-a actions (78% and 5% respectively), one as A-a action (2% and 0.14%), and seven as C-a actions (16% and 1%). There were eight assigned F-a actions under the FA category (18% and 1%), five U-A codes (11% and 0.72%), ten V-a codes (23% and 1%), and 21 W-a codes (48% and 3%). Finally, of the CA codes, there were three E-a codes (4% and 0.43%), 29 G-a (47% and 4%), eight K-a (12% and 1%), ten I-a (15% and 1%), and 18 S-a (27% and 3%).

Links and networks

P-2's design process logged 19 types of back-links total with 11 of these being DVm to VG links, and the total matrix for the back links in the entire design process can be found in Table 8.5. Ten types of back links total were recorded during the BRS stage, nine during the

GEN stage, six during EVA, and 11 during DEV, the networks of which can be found in Appendix 16. There was a shared network of back links for P-2's design process of VG to VT links only.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	6	0	0	0	0	0	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	11	0	0	0	0	7	0	6	0	2	2	9	0
VI	0	0	0	1	0	0	2	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	6	0	0	0	0	3	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	1	0	7	0	0	2	0	0	0	0	0	1	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	3	0	0	0	0	0	0	0	0	0	0
PM	0	0	0	5	0	0	0	0	2	0	0	0	0	0
PI	0	0	0	1	0	0	0	0	0	0	0	0	0	0

Table 8.5: Back imagery links for P-2

For other imagery links, there were 27 types recorded total of which ten were VG to VP links and eight VG to PM links, as can be seen in Table 8.6. There were 11 types found during the BRS stage, ten during GEN, six during EVA, and 16 throughout the DEV stage, the full networks of which can be found in Appendix 16. The only shared network connected between the stages is VG to VP.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	2	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	1	0	0	0	0	1	0	0	0	3	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	0	0	0	0	0	3	0	4	0	0	0	0	0
VI	0	0	0	0	0	0	0	0	1	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	2	0	1	0	0	0	0	1	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	4	0	10	0	0	4	0	0	0	0	0	3	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	2	0	0	0	0	0	0	0	0	0	0
PP	0	1	0	1	0	0	0	0	0	0	2	0	2	0
PM	0	5	0	8	0	0	4	0	1	0	0	1	0	0
PI	0	0	0	4	0	0	0	0	3	0	0	0	2	0

Table 8.6: Other imagery links for P-2

Over the entire design process, P-2 logged 149 total concurrent imagery-action links with 60 total types, the total matrix of which can be seen in Table 8.7. There were 80 total imagery links with PhA codes across 30 types. Additionally, there were 27 imagery-PeA links recorded across 8 types, 13 imagery-FA links across eight types, and 29 imagery-CA links across 14 types. Of these, the only shared network across all stages was VG:Ds-a links.

During the BRS stage there were 37 links logged across 22 types, with 20 links found for PhA codes over ten types. A further three codes were logged over three types for PeA, three across two for FA, and 11 across seven for CA codes. 38 links were recorded across 18 types

during the GEN stage. 20 of these were PhA codes over eight types, five were PeA codes across three types, three were FA codes over three types, and two were CA codes across two types. An additional 26 links were found during EVA with 18 types, 16 PhA codes with ten types, five PeA codes with three types, three FA codes with three types, and two CA codes with two types. Lastly, 48 of the 149 links were recorded during the DEV stage with these being split across 25 types of links. There were 24 PhA links over 13 types, 14 PeA across five, four FA across two, and six CA across five types. The networks for each design stage can be found in Appendix 16.

Action	Imagery													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	4	0	0	0	0	0	0	0	0	0	1	0	0
Da	0	0	0	3	0	0	0	0	0	0	0	0	0	0
Ds	0	6	0	18	0	0	6	0	5	0	0	0	6	0
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0	5	0	0	1	0	2	0	0	0	1	0
Lp	0	1	0	2	0	0	2	0	1	0	2	1	1	0
Lb	0	0	0	0	0	0	0	0	1	0	0	0	1	0
H	0	1	0	1	0	0	0	0	0	0	0	0	0	0
Hd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hp	0	0	0	0	0	0	1	0	0	0	1	0	0	0
M	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Mp	0	0	0	1	0	0	1	0	2	0	0	0	1	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	1	0	0	0	0	0	0	0	0	0	0
O	0	1	0	13	0	0	6	0	1	0	0	0	0	0
A	0	0	0	1	0	0	0	0	0	0	0	0	0	0
C	0	0	0	2	0	0	0	0	2	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	2	0	0	0	0	3	0	0	0	0	0	0	0
U	0	2	0	1	0	0	0	0	0	0	0	0	0	0
W	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	0	0	0	0	0	1	0	0	0	0	0
V	0	0	0	2	0	0	0	0	0	0	1	0	0	0
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G	0	0	0	2	0	0	0	0	1	0	0	1	3	0
K	0	0	0	1	0	0	1	0	0	0	0	0	6	0
I	0	0	0	1	0	0	0	0	3	0	0	0	0	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	5	0	2	0	0	1	0	1	0	0	0	1	0

Table 8.7: Concurrent imagery links for P-2

8.6.3 Participant 3

Occurrence

For P-3, the total design time was 20 minutes and 25 seconds, with an average of 3.48 seconds per segment across 352 segments. There were 64 imagery codes in total, along with 583 action codes. 18% of segments received an imagery code, with only one of these not receiving a concurrent action code (0.28%). 99% of segments received at least one action code,

with only one segment remaining uncoded (0.28%). A total of 82% of all segments were coded only with action codes, while 18% of segments received both imagery and action codes, and there were an average of 0.18 imagery and 1.66 action codes for any one segment.

During the BRS stage of the design process, P-3 had 87 segments categorised across five minutes and 22 seconds. This calculated to an average of 3.70 seconds for each segment. In total, there were 16 imagery codes and 154 action codes assigned across the segments, with all 87 segments receiving at least one action code. 18% of segments were assigned an imagery code, and all of these were also assigned one or more action codes. There were 0.18 imagery codes and 1.77 action codes per segment on average. The GEN stage occurred over six minutes and 52 seconds with 111 segments total and an average of 3.70 seconds per segment. There were 22 imagery codes which accounted for 20% of segments; one of these was assigned as imagery-only (0.90%). 98% of segments were assigned action codes, with one segment left uncoded (0.90%). Of the 111 segments, 79% were assigned action-only codes and 19% were assigned both imagery and action codes. An average of 0.20 imagery and 1.60 action codes were calculated per segment. A further 86 segments were categorised for the EVA stage across six minutes and 15 seconds and at an average of 4.40 seconds for each segment. There were 15 imagery and 135 action codes found, with 17% of all segments receiving an imagery code, all of which also received concurrent action codes. All 86 segments received at least one action code, with no segments left uncoded. 0.17 imagery codes were found on average per segment, along with 1.57 action codes. Lastly, P-3's DEV stage logged 68 segments across ten minutes and 24 seconds at an average of 9.20 seconds per segment. The stage logged 11 imagery and 116 action codes. 16% of all segments received an imagery code, all of which also received at least one action code. There were zero uncoded segments with 100% of all segments being assigned one or more action codes, 84% of which were purely action segments. There were an average of 0.16 imagery and 1.71 action codes for every one segment.

In total across P-3's entire design process there were 64 imagery codes recorded, 47 of which were indexed as new codes (73%), 17 as continued (27%) and zero as revised. Overall, there were five Dx codes logged (8%), 40 Vx codes (62.50%), and 19 Px codes (29.50%). Of the Dx codes, all were assigned as DVm codes, with two being indexed as new (40%) and three as continued (60%). There were no VI, VS, VR or VX codes assigned under the Vx viewpoint, while 24 were logged as VG (accounting for 60% of all Vx codes recorded and 37.50% of all imagery codes). A further 13 VT codes were recorded (32.50% and 20%

respectively), two VP codes (5% and 3%), and one VF code (2.50% and 2%). Of these 40, 34 were indexed as new codes (85%) and six as continued (15%). In addition, there were zero PP codes recorded, 15 PM codes (79% of all Px codes and 23% of all imagery codes), and four PI codes (21% and 6% respectively). 11 of these codes were new (58%) and eight were continued (42%).

During P-3's BRS stage there were 16 recorded imagery codes, of which none were assigned in the Dx viewpoint, nine in Vx (56%), and seven in Px (44%). Of the Vx assigned codes, five were VG codes and four were VT, and of the Px assigned codes, all seven were PM. For the GEN stage there were 22 imagery codes assigned, with five Dx total (23%), 12 Vx (54%), and five Px (23%). Seven were VG, four VT, and one VP, alongside all five of the Px codes being categorised as PM. There were 15 imagery codes found in the EVA stage, with none being in the Dx category. Eight were in the Vx category (53.33%): two VG, five VT, and one VP. A further seven were assigned Px codes (46.67%): three PM and four PI. Finally, the total imagery codes for the DEV stage was 11, all of which were assigned as Vx codes, with ten of these being VG codes and one VF code.

There was a sum total of 583 action codes assigned to P-3's entire design process, with 292 new indexed codes (50%), 241 continued (41%) and 50 revised (9%). There were 474 assigned PhA codes (81%), 16 PeA (3% - all of which were categorised by the O-a code only), 31 FA (5%), and 62 CA (11%), with the cognitive-defined actions totalling 109 (19%). Of the PhA codes, 189 were assigned to the D-a category which accounts for 40% of all PhA codes, and 32% of all action codes. Further to this, 67 were assigned L-a (14% and 11% respectively), 14 as H-a (3% and 2%), 82 as M-a (17% and 14%), nine as N-a (2% and 1.50%), and 113 as X-a (24% and 19%).

The breakdown for the FA category was nine for F-a codes (29% of all FA codes and 2% of total action codes), five for U-a (16% and 0.86% respectively), one for V-a (3% and 0.17%), and 16 for W-a (51% and 3%). There were zero I-a assigned codes in the CA category, with one assigned E-a (2% of all CA codes and 0.17% of all imagery codes), 19 G-a (31% and 3% respectively), 11 K-a (18% and 2%), and 31 S-a (50% and 5%).

Links and networks

There were 18 types of imagery back links found through P-3's design process which can be seen in full in Table 8.8, and of which 14 were PM to VG. Five types of back imagery

links were found during the BRS stage, ten during GEN, six during EVA and four for DEV, the networks of which can be found in Appendix 17. There was a single shared network connection of VG to PI for all stages of the design process.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	2	0	0	1	0	0	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	2	0	0	0	0	11	0	1	0	0	0	14	4
VI	0	0	0	5	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	1	0	0	0	0	0	0	0	0	1	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	0	0	1	0	0	0	0	0	0	0	0	0	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	1	0	0	0	0
PM	0	1	0	4	0	0	0	0	1	0	0	0	0	0
PI	0	2	0	11	0	0	1	0	0	0	0	0	0	0

Table 8.8: Back imagery links for P-3

In total there were 15 types of other imagery links found overall in the design process for P-3, with 18 of these being VG to PM. The full matrix for this can be found in Table 8.9. Five other links were found during the BRS stage, ten during GEN, eight during EVA and two during DEV, with the full networks in Appendix 17. There was an additional single shared network connection of VG to PM for P-3's other links.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	2	0	0	0	0	0	0	1	1	0	0	1	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	0	0	0	0	0	0	0	0	0	0	0	2	1
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PM	0	2	0	18	0	0	4	0	0	0	0	0	0	3
PI	0	1	0	5	0	0	9	0	1	0	0	0	11	0

Table 8.9: Other imagery links for P-3

There were 100 total concurrent imagery-action links throughout the design process, over 41 types of links, the full matrix of which is found in Table 8.10. 53 of the 100 were categorised under the PhA codes, with 22 types. A further six were under PeA codes, with four types, 12 were under the FA codes, with seven types, and 39 were under the CA codes, with eight types and including 11 PM:K-a links. There was a single shared network of VG:Ds-a links.

Throughout the BRS stage there were 31 concurrent imagery-action links over 15 types. 16 links were PhA assigned with nine types, one was PeA assigned, zero were FA assigned, and 14 were CA assigned with five types. For the GEN stage there were 41 concurrent links found with 22 types in total. 21 of these were PhA links over 12 types, one was a PeA assigned link, nine were FA links over four types, and ten were CA links over five types. Further, 29 links were found during EVA across 17 types, with 15 of these being PhA codes across ten types, two PeA codes across two types, one FA code, and 11 CA codes across four types. Finally, 22 concurrent links were found during the DEV stage with nine types of links total. PhA codes accounted for 11 of these with five types, two PeA codes with only one type, two FA codes across two types, and seven CA codes with only one type. All networks per stage can be found in Appendix 17.

Action	Imagery													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	0	0	8	0	0	1	0	0	0	0	0	6	0
Da	0	2	0	2	0	0	2	0	0	0	0	0	5	1
Ds	0	3	0	9	0	0	5	0	0	1	0	0	0	1
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0	1	0	0	0	0	1	0	0	0	1	0
Lp	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lb	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Hd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hp	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mp	0	0	0	4	0	0	4	0	1	0	0	0	2	2
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X	0	0	0	1	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O	0	1	0	2	0	0	2	0	1	0	0	0	0	0
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	3	0	4	0	0	0	0	0	0	0	0	0	0
U	0	0	0	1	0	0	0	0	1	0	0	0	1	1
W	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G	0	0	0	7	0	0	1	0	0	0	0	0	1	0
K	0	0	0	0	0	0	0	0	0	0	0	0	11	0
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	1	0	9	0	0	7	0	0	0	0	0	2	3

Table 8.10: Concurrent links for P-3

8.6.4 Participant 4

Occurrence

P-4's entire design process time totalled 33 minutes and 50 seconds, with a total of 503 segments categorised. This calculates to approximately 4.00 seconds for every segment. There were 102 total imagery codes and 817 action codes, with zero segments remaining uncoded. All 503 segments were assigned at least one action code, and 21% of the segments were assigned an imagery code, of which all imagery coded segments received a concurrent action code. 79% of all segments were recorded as action-only segments. There were approximately 0.20 imagery codes and 1.62 action codes per segment.

There were 78 categorised segments during P-4's BRS design stage over the course of five minutes and 13 seconds, averaging approximately 4.00 seconds for each segment. 17 imagery codes were assigned during BRS, as well as 125 action codes, with no segments remaining uncoded. All 22% of segments coded with imagery codes were assigned concurrent action codes, and all 78 segments received at least one action code. 78% of all segments were assigned action-only codes, with an average of 0.22 imagery and 1.60 action codes per segment. Over the 12 minutes and 25 seconds GEN time, 185 segments were undertaken, with 42 imagery codes and 308 action codes assigned. There was an average segment time of 4.00 seconds. All 185 segments were allocated action codes, with 23% of segments allocated imagery codes, and all of these receiving concurrent action codes. 77% of segments were assigned as action-only, and there was an average of 0.23 imagery codes and 1.66 action codes per segment during the stage. Four minutes exactly was spent on the EVA stage of the design process, at approximately 3.20 seconds for each of the 76 segments recorded. There were 13 imagery codes and 123 action codes total, with all 76 segments receiving at least one action code. All 13 imagery codes also had corresponding action codes, and there were zero uncoded segments. 82% of all segments received an action code without any imagery code, and there was an average of 0.17 imagery and 1.62 action codes per segment. Lastly, 164 segments were categorised for the DEV stage over 12 minutes and 12 seconds, at an average of 4.50 seconds per segment. There were 30 imagery codes and 261 action codes total for the stage, and all 30 imagery codes had corresponding action codes, while all 164 segments were assigned action codes. 18% of segments received imagery codes, and 82% of segments were recorded with action codes alone. The average number of codes per segment were 0.18 imagery and 1.59 action.

P-4's design process was categorised by 102 total imagery codes across all design stages, with 57 codes indexed as new (56%), 45 as continued (44%), and zero as revised. 16 codes were assigned in the Dx viewpoint (16%), 77 as Vx (75%), and nine as Px (9%). There were no DV or DVv assigned codes, with 14 DVm codes (87.50% of all D codes and 14% of all imagery codes), and two DVe code (12.50% and 2% respectively). The index of all Dx codes were seven new codes (44%) and nine continued codes (56%). Further, there were no VS, VR, VF or VX codes and an index of 45 new codes (58%) and 32 continued codes (42%) for all Vx-category recorded codes. There were 37 VG codes (48% of all Vx codes and 36% of all imagery codes), one VI code (1% and 0.98% respectively), 23 VT codes (30% and 23%), and 16 VP codes (21% and 16%). Lastly, there was one recorded PP code accounting for 11% of all Px codes and 0.98% of all imagery codes, eight PM codes (89% and 8% respectively), and no recorded PI codes. The index for Px-categorised codes was five new (56%) and four continued (44%).

For P-4's BRS stage, there was a total of 17 segments recorded, with six assigned Dx codes (35%), nine Vx codes (53%) and two Px codes (12%). All Dx codes were recorded as DVm, and all Vx codes were recorded as VG. For the Px-category, there was one each recorded code for PP and PM, and zero PI codes. There were 42 total imagery codes assigned in the GEN stage, with eight Dx codes (19%), 30 Vx codes (71%), and four Px codes (10%), all of which were categorised as PM. Seven codes were DVm, while one of the eight Dx codes was assigned DVe. Of the Vx-categorised codes, eight were assigned VG, one was assigned VI, 16 were VT, and five were VP. The only recorded code for all 13 segments categorised in the EVA stage was VG, no other imagery codes were assigned throughout the stage. Finally, for P-4's DEV stage there were 30 total segments, of which two were Dx-coded (7%), 25 were Vx-coded (83%), and three were Px-coded (10%), all sub-coded as PM. There was one apiece for DVm and DVe subcodes. For the Vx-coded segments, seven each were coded VG and VT, and 11 were coded VP.

P-4's design process recorded a total of 817 action codes across the entire design time, with 389 of these indexed as new actions (48%), 375 as continued (46%), and 53 as revised (6%). Of the 817, 644 were assigned as PhA codes (79%), 38 as PeA (5%), 74 as FA (9%), and 61 as CA (8%). In total, there were 173 codes across the cognitive action categories at 21% of total codes. For the PhA category, there were 263 codes assigned with a D-a code accounting for 41% of all PhA codes and 32% of all action codes, 119 L-a codes (19% and 15%

respectively), 13 H-a codes (2% and 1.50%), 113 M-a codes (18% and 14%), two N-a codes (0.31% and 0.24%), and 134 X-a codes (21% and 16%).

There were no assigned A-a codes in the PeA category, with the codes categorised as three P-a (8% of PeA codes and 0.37% of all action codes), 23 O-a (61% and 3% respectively), and 12 C-a (32% and 2%). Further to this there was 13 F-a codes in the FA category (18% of all FA codes and 2% of all action codes), eight U-a codes (11% and 0.98% respectively), 13 V-a codes (18% and 2%), and 40 W-a codes (54% and 5%). Lastly, there was one E-a code in the CA category accounting for 2% of all CA codes and 0.12% of all action codes, 24 G-a codes (40% and 3% respectively), eight K-a codes (13% and 0.98%), six I-a codes (10% and 0.73%), and 22 S-a codes (36% and 3%).

Links and networks

The total number of types of imagery back links for P-4's design process was 24, with the full matrix of back links found in Table 8.11. These links include 14 VT to VG and VG to PM. By stage, there were nine types of back links during the BRS stage, 17 during GEN, one during EVA and 11 during DEV, with the full set of networks for each stage found in Appendix 18. P-4 recorded no shared network connections in their imagery back links throughout the entire design process.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	1	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	7	0	0	2	0	2	0	0	0	2	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	8	1	0	0	0	14	0	11	0	0	0	5	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	3	0	7	0	0	0	0	2	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	2	0	6	0	0	5	0	0	0	0	0	0	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	1	0	0	0	0	0	0	0	0	1	0
PM	0	1	0	14	1	0	2	0	1	0	0	0	0	0
PI	0	0	1	1	0	0	0	0	0	0	0	0	0	0

Table 8.11: Back imagery links for P-4

There were a total of 27 types of other imagery links in P-4's design process, as can be seen in Table 8.12 and including 11 VT to VP links. Further to this, the BRS stage had nine recorded link types, GEN 16 types, and DEV 15 types. The EVA stage of P-4's design process had no recorded other imagery links at all, and all networks for each stage can be found in Appendix 18. As previously, there were no shared network connections of other links between the stages.

	Imagery codes													
Links	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	1	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	0	0	0	2	0	1	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	5	1	0	0	0	5	0	2	0	0	0	3	0
VI	0	0	0	1	0	0	1	0	1	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	3	0	2	0	0	0	0	3	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	5	0	8	0	0	11	0	0	0	0	0	2	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0	0	0	1	0
PM	0	1	0	10	0	0	1	0	4	0	0	0	0	0
PI	0	0	0	2	0	0	3	0	5	0	0	0	2	0

Table 8.12: Other imagery links for P-4

There was a total of 198 concurrent links between imagery and action codes during P-4's design process, across 55 different types. In total, there were 104 PhA imagery-action codes logged across 25 types, including 17 VG:Ds-a and VT:Ds-a links, with the full matrix found in Table 8.13. In addition, there were 28 PeA concurrent links across seven types, including seven VT:O-a links, 27 FA links across 11 types, with six DVm:F-a links, and 39 CA links across 12 types, with eight VG:G-a and VG-S-a links. There were no shared concurrent imagery-action links across any of the stage networks for P-4.

For the BRS stage of the design task, P-4 logged 32 total links across 13 different types, with 16 of these being PhA links and five types. The only type of PeA link during BRS was two links for VG:O-a. There were also five links for FA across three types, and nine CA links across four types. There were 82 total links during the GEN stage across 35 types, including 44 PhA links across 19. Further, there were 16 links for PeA with five types, 10 FA links across four types, and 12 CA links across seven types. EVA recorded 25 links across five types, with only 13 PhA links across five types. There were no concurrent EVA links between imagery codes and PeA codes. There were four FA links with the only type being VG:V-a, and eight CA links with the only type being VG:G-a. Finally, there were 59 concurrent links across 31 types for the DEV stage of the design process. 31 of these links were for PhA codes across 13 types, and ten for PeA across five links. Eight links were recorded for FA codes across six types. Ten links were recorded for CA codes across seven types. The full set of networks for all stages of the design process can be found in Appendix 18.

	Imagery													
Action	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	0	0	4	0	0	0	0	1	0	0	0	0	0
Da	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ds	0	11	0	17	1	0	17	0	10	0	0	0	5	0
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	1	0	3	0	0	3	0	3	0	0	0	1	0
Lp	0	0	2	8	0	0	0	0	0	0	0	0	0	0
Lb	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	0	1	0	0	0	0	1	0	1	0	0	0	0	0
Hp	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Mp	0	1	0	4	0	0	3	0	2	0	0	0	2	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	3	0	0	0	0	0	0	0
O	0	0	0	6	0	0	7	0	3	0	0	0	0	0
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	2	0	0	1	0	6	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	6	0	2	0	0	4	0	0	0	0	0	0	0
U	0	0	0	1	0	0	3	0	2	0	0	0	0	0
W	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	1	0	0	1	0	2	0	0	0	0	0
V	0	0	0	4	0	0	0	0	0	0	0	0	0	0
E	0	0	1	0	0	0	0	0	0	0	0	0	0	0
G	0	2	0	8	0	0	0	0	0	0	0	0	1	0
K	0	0	1	0	0	0	0	0	0	0	0	0	7	0
I	0	0	0	1	1	0	0	0	2	0	0	0	0	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	5	0	8	0	0	2	0	0	0	0	0	0	0

Table 8.13: Concurrent links for P-4

8.6.5 Participant 5

Occurrence

Over the entire design process, P-5 logged a total of 496 segments over 35 minutes and 30 seconds, which calculates to approximately 4.30 seconds per segment. There were a total of 95 logged imagery codes and 857 action codes, with an average of 0.19 imagery codes and 1.73 action codes per segment. 19% of the segments were allocated an imagery code, with all of these segments also receiving at least one action code. Two segments remained uncoded, and 80% of all segments received action codes alone.

68 segments total were categorised for the BRS stage alone over a total time of five minutes and 30 seconds. This approximates to 4.90 seconds per segment, and there was an average of 0.28 imagery and 1.72 action codes for each segment. There were 19 imagery codes during the stage, alongside 117 action codes, and no segments remained uncoded. 28% of segments were assigned an imagery code, with all of these also receiving an action code, while 72% of segments were assigned action codes only. For the GEN stage there were a total of 142

categorised segments across the ten minutes and 58 seconds of design time. Each segment was approximately 4.60 seconds long and contained an average of 0.27 imagery codes and 1.81 action codes. There were 38 imagery codes and 257 action codes in the stage, with 27% of segments assigned an imagery code. All 142 segments received at least one action code, with 73% of segments receiving only action codes, and all imagery-coded segments also coded with action codes. The EVA stage of the design process was eight minutes and 34 seconds long with 121 total segments, making each segment approximately 4.30 seconds in length. There were 21 imagery codes and 205 action codes total, with two segments left uncoded (2%). 17% of all segments received an imagery code, and 98% received at least one action code, with 81% of segments being coded action-only. There were an average of 0.17 imagery and 1.69 action codes for each segment. Lastly, the DEV stage had 165 categorised segments over ten minutes and 28 minutes, at 3.80 seconds average segment time. There were 17 imagery codes logged and 278 action codes, with only 10% of segments allocated imagery codes, all of which also received action codes. All segments received action codes and no segments remained uncoded. There was an average of 0.10 imagery and 1.68 action codes for each segment.

The total imagery occurrence for the whole design process was 95, with 52 new imagery codes (55%), 43 continued imagery codes (45%), and no revised imagery segments. There were four Dx codes overall at 4%, made up of entirely DVm subcodes and indexed at two new and continued codes each. 46 Vx codes were recorded at 48% of the total, with 17 new codes (37%) and 29 continued codes (63%). There were no VI, VS or VX subcodes, while there were 22 VG codes at 48% of all Vx codes, and 23% of all imagery codes. There were a further 13 VT codes (28% and 14% respectively), one VR code (2% and 1%), eight VP codes (17% and 8%), and two VF codes (4% and 2%). Overall P-5 logged 45 Px codes accounting for 47% of the imagery codes, with 29 PP (64% of all Px codes and 31% of all imagery codes), 13 PM codes (29% and 14% respectively), and three PI codes (7% and 3%). There were 33 new Px codes (73%) and 12 continued codes (27%).

During the BRS stage, P-5 logged 19 total imagery codes, with one being in the Dx category (5% and coded as DVm), 16 being in the Vx category and two being in the Px category (11% and both coded as PM). The Vx category codes consisted of nine VG codes, two VT codes, one VR code, and four VP codes. There were 38 total imagery codes during the GEN stage of the design process, with three coded as Dx imagery (8%), and all of which were DVm codes. There were a further 19 Vx codes (50%), made up of nine VG codes, six VT

codes, and two each of VP and VF codes. 42% of the codes were coded as Px codes (16 total), with ten PP, five PM, and one PI code. Following this, the EVA stage consisted of no Dx or Vx codes, and 21 total imagery codes, all coded as Px. The categorisation for these was 18 PP codes, one PM code and two PI codes. Finally, the DEV stage again consisted of no Dx codes, with 11 of the overall 17 codes in the Vx category. These were categorised as four VG codes, five VT codes, and two VP codes. The remaining six codes in the DEV stage were Px-categorised codes, with one PP and five PM.

There was a total sum of 857 action codes across P-5's design process, with 404 of these indexed as new codes (47%), 422 as continued (49%), and 31 revised codes (4%). 667 codes were assigned in the PhA category (78%), 36 in PeA (4%), 104 in FA (12%) and 50 in CA (6%). There was a total of 190 cognitive-labelled codes at 22% of the total action codes. In the PhA category, 214 were assigned to the D-a code accounting for 32% of the total PhA codes and 24.97% of the total action codes. Further to this there were 148 L-a codes (22% and 17% respectively), 33 H-a codes (5% and 4%), 88 M-a codes (13% and 10%), 47 N-a codes (7% and 5%), and 137 X-a codes (21% and 16%).

For the PeA codes, there were zero logged for either the P-a or A-a subcodes, while 33 were recorded as O-a codes (92% and 4%) and three as C-a codes (8% and 0.35%). There were nine F-a codes in the FA category at 9% and 1%, with a further ten codes for U-a (10% and 1%), 17 for V-a (16% and 2%), and 68 for W-a (65% and 8%). Finally, while there were zero recorded I-a codes in the CA category, there were five E-a codes (10% and 0.58%), 21 G-a codes (42% and 3%), 14 K-a codes (28% and 3%), and ten S-a codes (20% and 1%).

Links and networks

In total P-5 logged 20 types of imagery back codes total as can be seen in the matrix in Table 8.14, with 26 PP to VG links. For the BRS stage, there were ten total types of back links, for GEN 12 types, for EVA three types, and for DEV seven types of back links. All networks by stage can be found in Appendix 19. There is one shared network connection between the stages of PM to VG.

	Imagery codes													
Links	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	3	0	0	0	0	0	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	2	0	0	0	0	8	0	6	2	0	26	12	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	0	0	0	0	1	1	0	0	0	0	1
VR	0	0	0	1	0	0	0	0	0	0	0	0	0	0
VP	0	0	0	5	0	0	4	0	0	0	0	0	0	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	2	0	0	0	0	0	0	0	0	0	2
PM	0	2	0	5	0	0	0	0	1	0	0	0	0	0
PI	0	0	0	4	0	0	1	0	0	0	0	0	1	0

Table 8.14: Back imagery links for P-5

There were 28 total types of other imagery links in P-5's design process data, with all links seen in Table 8.15, including six VG to PM. Networks for each design stage group of links can be found in Appendix 19. There were 11 types of links found in the BRS stage, 15 in the GEN stage, two in the EVA stage, and nine in the DEV stage. There were no shared network connections between the stages.

	Imagery codes													
Links	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	1	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	1	0	0	1	0	0	0	0	0	1	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	2	0	0	0	0	5	0	2	0	0	3	1	2
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	0	0	0	0	0	1	0	0	0	0	0
VR	0	0	0	2	0	0	0	0	0	0	0	0	0	0
VP	0	1	0	4	0	0	3	1	0	2	0	1	1	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	5	0	0	0	0	0	0	0	0	4	0
PM	0	1	0	6	0	0	0	0	0	0	0	0	0	1
PI	0	0	0	2	0	0	4	0	5	0	0	1	2	0

Table 8.15: Other imagery links for P-5

Over the course of P-5's design process, 189 total concurrent imagery-action links were logged across all stages and over 55 types of links. The full matrix can be found in Table 8.16 and includes 102 links found with PhA category links across 33 types, including 17 PP:L-a links. A further 18 links were found across five types in PeA with six for VG:O-a, 28 links across 15 types in FA with five for PP:W-a, and 41 links across 12 types in CA with 14 for PP:G-a. There were no shared network connections across the stages.

The BRS stage contains 38 total concurrent links over 23 types, with 19 PhA links across 11 types, and five PeA links across only two types, six for the FA category, and eight for the CA category. There were 46 total imagery-action links across 42 types found during the GEN stage. Additionally, eight were found for PeA across four types, 14 for FA across eight, and 12 for CA across seven. Following this, 40 links were found during the EVA stage

across nine different types. This was made up of 21 PhA category links over five types, zero PeA links at all, four FA links over two types, and 15 CA links over two types. Finally, 35 concurrent links were found during the DEV stage of the design process across 24 different types. 18 of these links were PhA category coded across 12 types of links, and five for PeA across three types. Additionally, six FA links were found over five types, and six CA links over four types. All networks for the concurrent codes can be seen in Appendix 19.

Action	Imagery													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	0	0	0	0	0	2	0	1	2	0	5	0	0
Da	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ds	0	4	0	12	0	0	8	1	5	0	0	3	2	0
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0	4	0	0	1	0	1	0	0	17	1	2
Lp	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Lb	0	0	0	0	0	0	0	0	0	0	0	1	2	0
H	0	0	0	2	0	0	0	0	0	0	0	3	0	0
Hd	0	0	0	1	0	0	0	0	0	0	0	0	1	0
Hf	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hp	0	0	0	0	0	0	0	0	0	0	0	1	1	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mp	0	0	0	4	0	0	2	0	0	0	0	0	1	1
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	0	0	2	0	0	0	0	1	0	0	3	5	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O	0	0	0	6	0	0	5	0	4	0	0	0	0	0
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	2	0	1	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	0	0	3	0	0	1	0	0	0	0	0	1	0
U	0	2	0	1	0	0	2	1	0	0	0	1	0	0
W	0	0	0	3	0	0	0	0	0	1	0	5	1	3
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	0	0	0	0	0	0	0	0	2	0	0
V	0	0	0	0	0	0	1	0	0	0	0	2	0	0
E	0	0	0	2	0	0	1	0	0	0	0	0	0	0
G	0	0	0	0	0	0	0	0	1	0	0	14	2	0
K	0	2	0	2	0	0	0	0	0	0	0	0	8	0
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	0	0	5	0	0	1	0	2	0	0	0	1	0

Table 8.16: Concurrent links for P-5

8.6.6 Participant 7

Occurrence

At 22 minutes and 35 seconds long, P-7's design process consisted of 308 categorised segments in total, calculated at an average of 4.40 seconds per segment. There were 76 imagery codes in total and 551 action codes, with only one uncoded segment (0.32%). 25% of segments were imagery coded with all receiving concurrent action codes. 99.50% of segments were coded with action-categories and 73% coded as action-only. There were an average of 0.25 imagery and 1.79 action codes for each segment.

The BRS design stage was undertaken over five minutes and 13 seconds with 74 total segments found. An average time of 4.20 seconds per segment has been calculated, with averages of 0.20 imagery and 1.78 action codes per segment. There were 15 imagery codes assigned and 132 action codes, with all 74 segments assigned at least one action code. 29% of segments were allocated an imagery code, and all of these were also categorised with action codes. There were 103 segments during the GEN stage over eight minutes and six seconds, with an average of 4.70 seconds per segment. The GEN stage consisted of 24 imagery codes and 173 action codes total, with all 103 segments containing action codes and 77% containing only action codes. 23% of segments were assigned imagery codes, with all of these featuring concurrent action codes. There were an average of 0.23 imagery and 1.68 action codes per segment. Following this the EVA stage contained 79 segments and ran over five minutes and 41 seconds. There was an average of 4.30 seconds per segment and all segments recorded at least one action code, with 59.50% of segments recording only action codes. 40.50% of all segments featured an imagery code alongside the action code. There were zero uncoded segments for any of the BRS, GEN and EVA stages. Lastly, the DEV stage ran over only three minutes and 35 seconds with 52 segments total and an average time of 4.10 seconds per segment. There were five imagery codes recorded and 90 action, with 10% of segments recording imagery codes, all of which had concurrent action codes. 98% of segments received an action code, and there was one uncoded segment at 2%, as well as an average of 0.10 imagery and 1.73 action codes for each segment.

The imagery occurrence for P-7 was a total of 76 imagery codes across all stages of the design process, with 66 codes indexed as new (87%), 10 continued codes (13%) and no revised codes. 11 of these 76 were logged for the Dx category at 15%, all of which were assigned DVm codes and with an index of eight new codes (73%) and three continued codes (27%). There were 30 Vx codes at 40%, with no subcodes of VI, VS, VR, VF or VX and an index of 23 new codes (77%) and seven continued (23%). The Vx codes were categorised as 24 VG codes accounting for 80% of the total Vx codes and 32% of the total imagery codes, five VT codes (17% and 7% respectively), and one VP code (3% and 1%). The Px codes totalled 35 (46%) and 100% of these were new indexed codes. There were no assigned PP codes, 34 PM codes (97% and 45%), and one PI code (3% and 1%).

There were 15 imagery codes total for the BRS stage of P-7's design process with five of these assigned as Dx codes (33.33% and all coded DVm). Further, eight were coded in the

Vx category at 53.33% and all coded VG, and two were coded Px at 13.33% and all coded PM. For the GEN stage there were 24 imagery codes total, with six DVm codes accounting for 25% of the codes, 17 Vx codes at 71%, and one PI code at 4%. The Vx codes were split into 14 VG codes and two VT codes. The EVA stage consisted of 32 codes, all of which were coded PM, and the DEV stage consisted of five codes, all of which were coded in the Vx category. Of these five, two were coded VG and three VT.

P-7's design process logged a total of 551 action codes with an index total of 278 new codes (50%), 258 continued codes (47%) and 15 revised codes (3%). There were 427 PhA codes (77.50%), 22 PeA codes (4%), 45 FA codes (10%), and 46 CA codes (8.50%). The cognitive action codes totalled 124 accounting for 22.50% of all action codes. The PhA codes were categorised into 203 D-a codes accounting for 48% of all PhA codes and 37% of all action codes, 80 L-a codes (19% and 15% respectively), four H-a codes (0.94% and 0.73%), 31 M-a codes (7% and 6%), two N-a codes (0.47% and 0.36%), and 107 X-a codes (25% and 19%).

There were no P-a or A-a codes logged in the PeA category, whilst there were 19 O-a codes recorded (86% and 3%) and three C-a codes (14% and 0.54%). For the FA category, five codes were logged as F-a (9% and 0.91%), three as U-a (5% and 0.54%), 36 as V-a (64% and 7%), and 12 as W-a (21% and 2%). Lastly, the CA category codes contained zero for the E-a code, 13 for G-a (28% and 2%), one for K-a and I-a each (2% and 0.18% each), and 31 for S-a (67% and 6%).

Links and networks

There were 13 imagery back links found for P-7 total, including 32 PM to PP links, and all of which can be seen in Table 8.17. Over the BRS stage P-7 logged a total of 15 links across six link types, 24 links over the GEN stage with ten types, 32 over EVA with only one type, and five during DEV with three types, with networks for each stage found in Appendix 20. P-7 had no shared network connections between the back links in any of the design stages.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	3	0	0	0	0	0	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	11	0	0	0	0	4	0	1	0	0	0	2	1
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	4	0	0	0	0	0	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	0	0	5	0	0	1	0	0	0	0	0	0	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	1	0	0	0	0	0	0	0	0	32	0
PM	0	0	0	9	0	0	0	0	0	0	0	0	0	0
PI	0	0	0	2	0	0	0	0	0	0	0	0	0	0

Table 8.17: Back imagery links for P-7

P-7's design process logged 14 other imagery link types, all of which can be found in Table 8.18, and which included 32 PM to VG links. There were 12 other imagery links during BRS across four types, 24 during GEN across 11 types, 32 during EVA with only one type, and five during DEV across four types. The networks for each stage of the design process can be found in Appendix 20, and there are no shared network connections between the links for P-7.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	1	0	0	2	0	0	0	0	0	1	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	0	0	0	0	0	0	0	0	0	0	0	32	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	3	0	0	0	0	0	0	1	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	0	0	1	0	0	0	0	0	0	0	0	0	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	5	0	0	0	0	0	0	0	0	0	0
PM	0	8	0	8	0	0	1	0	0	0	0	0	0	1
PI	0	0	0	7	0	0	2	0	0	0	0	0	0	0

Table 8.18: Other imagery links for P-7

Over the course of P-7's design process, there were a total of 152 concurrent imagery-action links recorded across 34 types of links. 79 links were recorded for PhA codes with 17 types of links total and including 32 PM:D-a links. A further 12 were found for PeA codes over five types with eight for VG:O-a, 39 for FA codes over six types with 32 for PM:V-a, and 22 for CA with six types and including 11 for VG:S-a, all of which can be seen in Table 8.19. There were no shared networks of concurrent links across any of the stages for P-7.

The BRS stage contained 28 concurrent links over nine types of links, including 15 for PhA over four different link types. There were then no concurrent links recorded for PeA codes, only one for FA codes, and a further 12 for CA codes with four link types. There were 48 links found over 19 types for the GEN stage of the design process, with 25 of these being

recorded for PhA codes (eight types), ten for PeA codes (five types), five for FA codes (three types), and eight for CA codes (three types). A further 64 codes were found during the EVA stage of the design process, over only two types, with 32 links and one type each for PhA and FA codes, and zero links recorded for PeA or CA codes. Finally, the DEV stage logged 12 concurrent links total across eight link types, with seven for PhA over five types, two for PeA with only one type, only one link for FA, and two for CA over one type. The networks for P-7 can be found in Appendix 20.

Action	Imagery													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	5	0	8	0	0	0	0	0	0	0	0	32	0
Da	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ds	0	5	0	14	0	0	2	0	1	0	0	0	0	1
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Lp	0	0	0	0	0	0	2	0	0	0	0	0	0	0
Lb	0	0	0	0	0	0	0	0	0	0	0	0	1	0
H	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Hd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hp	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Mp	0	0	0	2	0	0	1	0	0	0	0	0	1	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X	0	0	0	1	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O	0	0	0	8	0	0	1	0	0	0	0	0	0	1
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	1	0	0	0	0	1	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	3	0	0	0	0	1	0	0	0	0	0	0	0
U	0	0	0	1	0	0	0	0	0	0	0	0	0	0
W	0	0	0	1	0	0	1	0	0	0	0	0	0	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	32	0
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G	0	1	0	0	0	0	0	0	0	0	0	0	1	0
K	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	6	0	11	0	0	2	0	0	0	0	0	1	0

Table 8.19: Concurrent links for P-7

8.6.7 Participant 8

Occurrence

P-8 logged a total time of 19 minutes and 28 seconds for their design process, along with 340 categorised segments and an average segment length of 3.40 seconds. There were 64 logged imagery codes, an average of 0.19 per segment, and 590 action codes, an average of 1.74 per segment. Four segments remained uncoded accounting for approximately 1% of the total segments. 19% of segments received imagery codes, all of which were assigned

concurrent action codes, with 99% of all segments assigned action codes and 80% receiving action codes alone.

During BRS, there were 42 total segments and a time of two minutes and 21 seconds. This calculated to an average of 3.40 seconds for each segment, along with an average of 0.31 imagery codes and 1.71 action codes per segment. There were 13 imagery and 72 action codes total, with only one segment remaining uncoded (2%). 31% of all segments received an imagery code, along with 98% receiving an action code. All segments coded with imagery were also coded with actions, and 66.67% of all segments were coded action alone. The GEN stage categorised 153 segments over eight minutes and 41 seconds, at an average of 3.40 seconds per segment. With 24 imagery and 265 action codes total, there were an average of 0.16 imagery and 1.73 action codes for each segment. 16% of all segments received an imagery code, with all of these coded concurrently with action, and only two segments remained uncoded (1%). There were 99% of segments assigned with action codes, with 83% receiving no concurrent imagery codes. P-8 logged 79 segments for the EVA stage over three minutes and 35 seconds, with 15 imagery and 144 action codes total. This calculates to an average of 2.70 seconds, 0.19 imagery codes and 1.82 action codes for each segment. 19% of segments received an imagery code alongside an action code, and all segments received action codes, with no segment remaining uncoded. Finally, for the DEV stage, there were 66 segments total over a design time of four minutes and 51 seconds, with 4.40 seconds average for each segment. There were 12 imagery and 109 action codes, with an average of 0.18 imagery and 1.65 action codes per segment. 18% of all segments received an imagery code and an action code, 99% of segments received an action code, and only one segment remained uncoded (1%).

Over P-8's design process, there were a sum total of 64 imagery codes assigned with 41 indexed as new codes (64%), 23 as continued (36%), and none as revised codes. 15 codes were recorded for the Dx-category (23%), with all of these recorded as DVm, 37 for the Vx-category (58%), and 12 for the Px-category (19%), with all of these recorded as PM only. 11 of the 37 Vx codes were assigned as VG, accounting for 30% of all Vx codes and 17% of all imagery codes, eight at VT (22% and 13% respectively), and 18 as VP (49% and 28%). There were no recorded codes for DV, DVv, DVe, VI, VS, VR, VF, VX, PP or PI subcodes. Four Dx codes were indexed as new (27%) and 11 as continued (73%), while 30 Vx codes were indexed

as new (81%) and seven as continued (19%), and seven Px codes as new (58%) and five as continued (42%).

For the BRS stage, 13 total imagery codes were logged with four each for Dx (DVm only) and Px (PM only) categories (at 31% each), and five for the Vx category (39%). Two codes were recorded as VT and three as VP. There were 24 codes total during the GEN stage, with six each logged for Dx (DVm only) and Px (PM only) categories at 25% of all GEN codes each. A further 12 were recorded for Vx codes (50%), with VG logging ten codes and two for VP. 15 codes were assigned during EVA with only one recorded for Dx (DVm) at 7%, 14 for Vx at 93%, and there were zero codes assigned as Px. One VG code was recorded, four VT codes, and nine VP codes. Lastly, for the DEV stage there were 12 logged imagery codes with four for Dx (33%, DVm only), six for Vx codes (50%) and two for Px codes (17%, PM only). The Vx codes were categorised into two VT subcodes and four VP codes.

There was a sum total of 590 action codes over P-8's entire design process, with 289 of these indexed as new (49%), 256 as continued (43%) and 45 as revised (8%). Of the 590, 446 were recorded as PhA codes (76%), 20 as PeA (3%), 50 as FA (9%), and 74 as CA (13%), with a combined total of 144 (24%) cognition-associated actions. 112 of the PhA category codes were assigned as D-a codes at approximately 25.11% of all PhA codes and 19% of all action codes. A further 127 were assigned L-a (28% and 22% respectively), 37 H-a (8% and 6%), 33 M-a (7% and 6%), 54 N-a (12% and 9%), and 83 X-a (19% and 14%).

In the PeA category, one each was recorded as P-a and A-a codes (5% and 0.17% each), eight as O-a (40% and 1%), and ten as C-a (50% and 2%). Additionally, 14 were recorded as F-a in the FA category (28% and 2%), four as U-a (8% and 0.68%), eight as V-a (16% and 1%), and 24 as W-a (48% and 4%). Finally, eight CA codes were assigned as E-a subcodes (11% and 1%), 21 as G-a (28% and 4%), seven as K-a (10% and 1%), 18 as I-a (24% and 3%), and 20 as S-a (27% and 3%).

Links and networks

In total, there were 18 types of imagery back links found for P-8's design process codes, with 13 of these recorded as VP to VG. The total matrix can be seen in Table 8.20, with all stage networks located in Appendix 21. Six types of links were found for the BRS stage, 14 for the GEN stage, six for EVA and finally nine were found during the DEV stage. The only shared network connection of back links was VP to VG.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	1	0	0	0	0	2	0	0	0	3	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	6	0	0	0	0	4	0	13	0	0	0	4	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	2	0	0	0	0	0	0	0	0	0	0
VR	0	0	0	2	0	0	0	0	0	0	0	0	0	0
VP	0	5	0	0	0	0	4	0	0	0	0	0	2	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0	0	0	3	0
PM	0	3	0	1	0	0	0	0	3	0	0	0	0	0
PI	0	1	0	5	0	0	0	0	0	0	0	0	0	0

Table 8.20: Back imagery links for P-8

20 other imagery links were found across the full design process, with eight of these logged as VP to PM links, and the entirety of which can be found in Table 8.21. All networks per design stage can be found in Appendix 21 and show six types of links for BRS, ten for GEN, eight for EVA, and eight for DEV. There were no shared network connections for other links across any of the design stages.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	5	0	0	1	0	0	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	5	0	0	0	0	4	0	3	0	0	0	4	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	0	0	0	0	0	1	0	0	0	1	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	0	0	2	0	0	0	0	0	0	0	0	1	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	1	0	0	0	0	0	0	0	0	0	0	0	0
PM	0	2	0	2	0	0	1	0	8	0	0	0	0	0
PI	0	7	0	2	0	0	2	0	6	0	0	0	2	0

Table 8.21: Other imagery links for P-8

There were 127 concurrent imagery-action links found across 54 types of links during P-8's design session, all of which can be seen in Table 8.22. A total of 70 links were recorded against PhA codes with 28 types of links total, 12 for PeA codes with six types, 14 for FA codes with seven types, and 31 for CA codes with 13 types. These included seven VG:Ds-a links, six VP:C-a, two VG:F-a, and five VG:S-a. There were no shared network connections found for the concurrent links.

The BRS stage of the design session had 24 recorded concurrent links total across 14 types, with 12 PhA across six types, four PeA across two types, none recorded for FA, and eight CA across six types. Following this, 49 links were found during GEN with 24 different types of links. 26 of these were assigned PhA codes with 14 types, three PeA codes with two types, nine FA codes with four types and 11 CA codes with four types. 32 concurrent links

across 17 types were seen in the EVA stage, with 19 across ten for PhA, two for PeA across only one type, only one for FA, and ten across five for CA. Finally, 21 links were found during DEV with 18 types total, 12 of which were for PhA codes with 19 types, three for PeA with three types, four for FA with four types, and two for CA with two types. The networks by stage of the total concurrent links can be found in Appendix 21.

Action	Imagery													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Da	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ds	0	4	0	7	0	0	0	0	4	0	0	0	3	0
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	4	0	0	0	0	1	0	0	0	0	0	1	0
Lp	0	1	0	0	0	0	3	0	5	0	0	0	0	0
Lb	0	1	0	0	0	0	2	0	0	0	0	0	2	0
H	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Hd	0	1	0	0	0	0	0	0	1	0	0	0	2	0
Hf	0	1	0	1	0	0	1	0	0	0	0	0	0	0
Hp	0	0	0	0	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mp	0	0	0	2	0	0	0	0	2	0	0	0	2	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	5	0	2	0	0	2	0	7	0	0	0	2	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	1	0	0	0	0	0
O	0	0	0	2	0	0	1	0	1	0	0	0	0	0
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	0	0	0	1	0	6	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	5	0	2	0	0	1	0	2	0	0	0	0	0
U	0	1	0	1	0	0	0	0	1	0	0	0	0	0
W	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	0	0	0	0	0	0	0	0	0	1	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G	0	2	0	0	0	0	1	0	0	0	0	0	2	0
K	0	0	0	0	0	0	0	0	0	0	0	0	4	0
I	0	1	0	1	0	0	0	0	4	0	0	0	2	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	2	0	5	0	0	4	0	1	0	0	0	2	0

Table 8.22: Concurrent links for P-8

8.6.8 Participant 9

Occurrence

With an average time of 3.90 seconds per segment, P-9 logged a total of 398 segments across the design session and 25 minutes and 36 seconds of design time. There were 116 imagery codes logged overall, an average of 0.29 per segment, and 713 action codes, an average of 1.79. There were no uncoded segments and all 398 codes received at least one action code. 29% of segments were coded with both imagery and action codes, and 71% with action codes alone.

The BRS stage of P-9's design process recorded 80 segments total over five minutes and six seconds, leading to an average segment time of 3.80 seconds. There were 23 imagery codes and 135 action codes, with all 29% of segments recording both an imagery and action code, and 71% recording action codes only. This led to approximately 0.29 imagery and 1.69 action codes per segment. The GEN stage was completed over five minutes and five seconds, with 85 categorised segments and an average segment time of 3.60 seconds. With 28 imagery and 146 action codes logged, there were an average of 0.33 imagery and 1.72 action codes for each segment. 33% of segments logged both imagery and action codes, with 67% logging only action codes. There were 80 segments recorded for the EVA stage over the five minutes and two seconds design time, with 16 imagery and 152 action codes total. This led to an average segment time of 3.80 seconds, and an average of 0.32 imagery and 1.83 action codes per segment. 20% of segments recorded both imagery and action codes, while 80% recorded action codes only. Lastly, the DEV stage recorded 153 categorised segments over ten minutes and 25 seconds, with an average of 4.10 seconds per segment. There were 49 imagery codes recorded (an average of 0.32 per segment) and 280 action codes (an average of 1.83). 32% of all segments logged an imagery and action code, while 68% were action alone.

The total 116 imagery codes during the design process were indexed as 56 new codes (48%) and 60 continued (52%), with no imagery codes indexed as revised. 22 were assigned Dx category codes (19%), 60 Vx category (52%) and 34 Px category (29%), with no subcodes recorded for DV, DVv, VS, VX and PI. The Dx category codes consisted of 21 DVm codes (96% of all Dx codes and 18% off all imagery codes) and only one DVe code (5% and 0.86% respectively), with an index of 13 new (59%) and nine continued (41%). 19 of the Vx codes were assigned as VG (32% and 16%), five as VI (8% and 4%), 17 each as VT and VP (28% and 15% each), and one each as VR and VF (2% and 0.86% each). The index breakdown for Vx codes were 31 new codes (52%) and 29 continued codes (48%). There was only one PP recorded code at 3% and 0.86% of codes, and 33 PM codes (97% and 29%), with a Px-index of 12 new (36%) and 22 continued (64%).

There were 23 allocated imagery codes during the BRS stage of the design process for P-9, with one assigned Dx (DVm) code (4%), two Vx codes (9%), and 20 Px (PM only) codes (87%). The Vx codes were categorised by one each for VG and VP codes. Of the 28 recorded imagery codes for the GEN stage, six were Dx category codes (21%, DVm only), 15 Vx category (54%), and seven Px category (25%, PM only). There were six VG codes, seven VT

codes, and two VP codes. During the EVA stage, out of the 16 total imagery codes, three were coded as Dx (19%, DVm only), 11 as Vx (69%), and two as Px (12%). The Vx codes were split into three VG codes, five VI codes, and three VP codes. Finally, there were 49 imagery codes total for the DEV stage of the design process, with 12 Dx codes (25%), 32 Vx codes (65%) and five Px codes (10%, PM only). The Dx codes were split into 11 DVm assigned codes and one DVe code. Nine of the Vx codes were assigned VG, ten VT, 11 VP, and one each for VR and VF.

P-9 logged a total of 713 action codes over the design session, with 304 indexed as new (43%), 374 as continued (53%) and 35 as revised (4%). There were 512 PhA codes logged (72%), 35 PeA (5%), 88 FA (12%) and 78 CA (11%), with a total of 201 (28%) cognitive-defined codes. Of the PhA codes, 166 were assigned to the D-a category (32% of the overall PhA codes and 23% of all action codes), 167 to L-a (33% and 23% respectively), 92 H-a (18% and 13%), 39 M-a (8% and 4%), 25 N-a (5% and 4%) and 23 X-a (5% and 3%).

There were no A-a codes assigned in the PeA category, while one P-a code was reported (3% and 0.14%), 16 O-a codes (46% and 2%), and 18 C-a codes (51% and 3%). 25 F-a codes (28% and 4%) were assigned from the FA category, along with 26 U-a (30% and 4%), 14 V-a (16% and 2%), and 23 W-a (26% and 3%). Lastly, ten E-a codes were assigned from the CA category (13% and 1%), 17 G-a (22% and 2%), 15 K-a (19% and 2%), 16 I-a (21% and 2%), and 20 S-a (26% and 3%).

Links and networks

There were a total of 21 types of imagery back codes over P-9's entire design process which can be seen in Table 8.23 and includes 30 PM to VG links. Four of these link types were found in the BRS stage, eight in the GEN stage, nine in the EVA stage, and 15 in the DEV stage. All networks for each stage can be found in Appendix 22. There were shared network connections found throughout all four stages for VP to VG and PM to VG.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	6	0	0	1	0	0	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	9	0	0	0	0	9	0	16	1	0	0	30	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	5	0	0	0	0	0	0	0	0	0
VT	0	7	0	3	0	0	0	0	1	0	0	0	0	0
VR	0	0	0	0	0	0	1	0	0	0	0	0	3	0
VP	0	5	0	2	0	0	5	0	0	0	0	0	0	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PM	0	0	0	7	0	0	0	0	0	0	0	1	0	0
PI	0	0	1	1	0	0	1	1	0	0	0	0	0	0

Table 8.23: Back imagery links for P-9

For other imagery links, there were a total of 29 types found over the design stages overall, including 19 for PM to VP. The total matrix for other links can be seen in Table 8.24, with networks by design stage found in Appendix 22. 23 link types were reported for the BRS stage, 14 for GEN, seven for EVA and 21 for DEV, and there were no reported shared network connections between the stages for other links.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	1	0	0	2	0	1	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	7	0	0	0	0	5	0	0	0	0	0	0	0
VI	0	0	0	0	0	0	0	0	0	0	0	1	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	3	0	1	0	0	0	1	8	0	0	0	8	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	1	0
VP	0	5	0	2	0	0	2	0	0	0	0	0	19	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	8	0	0	0	0	2	1	0	0	5	0
PM	0	4	1	1	5	0	2	0	5	0	0	0	0	0
PI	0	2	0	4	0	0	6	0	1	0	0	0	0	0

Table 8.24: Other imagery links for P-9

With concurrent links throughout the design process, there was a sum total of 241 found over 86 types of links. 146 of these were found for PhA codes over 50 types, including 11 VT:Ds-a links, all of which can be seen in Table 8.25. There were a further 20 found for PeA codes over ten types, including six PM:C-a, 34 over ten types for FA, including six PM:U-a, and 41 over 18 types for CA, including 14 PM:K-a. Again, no shared network connections were found for links between stages.

There were 35 concurrent links total over 16 link types during the BRS stage of P-9's design process, with 23 of these over nine types for the PhA codes. A further seven were found over two types for PeA, six over one type for FA, and nine over four for CA. 57 links were then found for the GEN stage with 28 link types. There were 33 codes over 16 types for the PhA codes, only one link for the PeA codes, 13 links and six types for FA codes, and 11 links

with five types for CA codes. 35 linked codes were found during the EVA stage with 23 types total, 26 of these with PhA codes and over 17 types of links. There were no linked PeA codes found, four FA codes over two types, and five CA codes over four types. Lastly, there were 100 links found for the DEV stage of the design process with 63 types. 65 of these 100 were found for PhA codes with 28 types, 12 for PeA with seven types, 17 for FA with seven types, and 16 for CA with 11 types. All networks for concurrent links can be found in Appendix 22.

Action	Imagery													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	0	0	1	0	0	1	0	2	0	0	0	11	0
Da	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Ds	0	8	1	5	0	0	11	0	5	0	0	0	7	0
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	7	0	7	4	0	3	1	5	1	0	1	4	0
Lp	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lb	0	1	0	3	0	0	0	0	3	0	0	0	7	0
H	0	5	0	4	3	0	1	0	2	0	0	0	2	0
Hd	0	3	0	0	0	0	1	0	0	0	0	0	0	0
Hf	0	1	0	0	0	0	3	1	2	0	0	0	1	0
Hp	0	0	0	1	1	0	0	0	1	0	0	0	0	0
M	0	0	0	0	0	0	0	0	1	1	0	0	1	0
Mp	0	2	0	2	0	0	0	0	1	0	0	0	2	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	0	0	0	0	0	2	0	0	0	0	0	1	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O	0	0	1	2	0	0	1	0	2	0	0	0	0	0
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	2	0	0	1	0	5	0	0	0	6	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	6	0	3	0	0	5	0	2	0	0	0	0	0
U	0	5	0	0	0	0	0	0	3	0	0	0	6	0
W	0	0	0	5	0	0	0	0	0	1	0	0	0	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	0	0	0	0	2	0	0	0	2	0	0	0	0	0
E	0	1	0	1	0	0	1	0	0	0	0	0	0	0
G	0	2	0	0	0	0	1	0	0	0	0	0	2	0
K	0	0	0	0	0	0	0	0	0	0	0	0	14	0
I	0	1	0	2	1	0	1	0	1	0	0	0	1	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	1	0	2	0	0	6	0	1	0	0	0	2	0

Table 8.25: Concurrent links for P-9

8.6.9 Participant 12

Occurrence

P-12's design process logged 398 total segments across a total time of 35 minutes and nine seconds, giving an average segment length of 5.30 seconds. Over the entire design session, there were 95 imagery codes and 624 action codes logged, with only three segments left uncoded (0.75%). 24% of segments received an imagery code and 99% received an action code, with all imagery codes being assigned at least one concurrent action code. 75% of all

action codes were coded without imagery. There was an average of 0.24 imagery codes and 1.57 action codes per segment.

When considering the design process by stage, 45 segments were categorised for the BRS stage over four minutes and 58 seconds and with 16 total imagery codes and 72 action codes. This resulted in an average length of 6.60 seconds, an average of 0.36 imagery codes, and an average of 1.60 action codes per segment. 36% of all segments received an imagery code, with 100% of segments receiving action codes. 64% of segments were coded action only, and 36% were coded with both. The GEN stage totalled 99 segments and nine minutes and 25 seconds, with an average segment length of 5.70 seconds. There were 29 total imagery codes and 161 action codes, with 100% of segments receiving at least one action code. 29% of all segments received an imagery code alongside the action codes and there was an average of 0.29 imagery and 1.63 action codes per segment. Following this, 144 segments were categorised for the EVA stage, with 12 minutes and 52 seconds design time and 5.40 seconds per segment. 19% of segments were coded with imagery codes (27 codes total) and 99% with action codes (225 codes total). One segment remained uncoded (0.69%), and all imagery codes had corresponding action codes. There was an average of 0.19 imagery codes and 1.56 action codes for each segment. Finally, the DEV stage lasted ten minutes and 35 seconds and returned 110 total segments, with an average length of 5.80 seconds each. There were 23 imagery codes which accounted for 21% of segments and an average of 0.21 per segment. Additionally, there were 166 action codes accounting for 98% of segments and with an average of 1.51 each. Two segments remained uncoded (2%), all imagery codes had concurrent action codes, and 77% of segments were action-only coded.

A sum total of 95 imagery codes were recorded over the entire design process, with an index of 67 new (71%), 28 continued (29%) and zero revised. Nine of the 95 were assigned as Dx codes (10%), 62 as Vx codes (65%) and 24 as Px codes (25%), with all Dx codes being reported as DVm only. The index for Dx codes was four new (44%) and five continued (56%). There were no recorded codes for VI, VS, VF, VX, with 30 assigned as VG (49% of all Vx codes and 32% of all imagery codes). A further 15 were logged as VT (24% and 16% respectively), one as VR (2% and 1%) and 16 as VP (26% and 17%). Of the 62 Vx codes, 44 were recorded as new (71%) and 18 as continued (29%). Further, there were no PP codes, 22 PM codes (92% and 23%) and two PI codes (8% and 2%) with an index of 19 new (79%) and five continued (21%).

There were 16 imagery codes recorded for the BRS stage, with three Dx codes (19%, DVm only), nine Vx codes (56%) and four Px codes (25%, PM only). Six of the Vx codes were logged VG and three VP. A further 29 were logged during the GEN stage, with five Dx codes at 17% and all subcoded as DVm. 11 codes were logged as Vx (38%) and 13 as Px (45%). Of the 11 Vx codes, six were VG coded, three VP, and one each of VT and VR. For the Px codes, 12 were subcoded PM and one as PI. With the EVA stage, there were 27 imagery codes total, with only one of these assigned to the Dx codes (3%, DVm). 22 were assigned Vx codes at 82%, seven of which were VG, nine were VT, and six were VP. The final four were assigned Px codes (15%) and with three PM codes and only one PI code. For the DEV stage, 29 imagery codes were logged, with five DVm codes, six VG, one VT, one VR, three VP, 12 PM and one PI code.

P-12 reported a total of 624 action codes across the design process, of which 269 were indexed as new (43%), 311 as continued (50%), and 44 as revised (7%). 439 of the 624 were coded as PhA actions (70%), 38 as PeA (6%), 77 as FA (12%) and 70 as CA (12%). Of the PhA actions, 191 were assigned D-a codes (44% of all PhA codes and 31% of all action codes), 158 as L-a (36% and 25% respectively), nine as H-a (2% and 1%), 45 as M-a (10% and 7%), and 36 as X-a (8% and 6%) with zero allocated as N-a codes.

Further, there were three P-a codes in the PeA category at 8% and 0.48%, 26 O-a codes (68% and 4%), only one A-a code (3% and 0.16%) and eight C-a codes (21% and 1%). For the FA category there were 13 F-a codes (17% and 2%), two U-a codes (3% and 0.32%), 37 V-a codes (48% and 6%) and 25 W-a codes (32% and 4%). Finally, there were four E-a codes in the CA category (17% and 2%), two U-a codes (29% and 3%), 13 K-a codes (19% and 2%), 13 I-a codes (19% and 2%) and 20 S-a codes (29% and 3%).

Links and networks

There were 21 total types of back imagery links for P-12 across their entire design process, the matrix for which can be found in Table 8.26, and which included 20 PM to VG links. Eight of these were during the BRS stage, ten each during the GEN and EVA stages, and 11 during the DEV stage, with all networks found in Appendix 23. A shared network connection across all stages was found with links VP to VG and PM to VG.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	9	0	0	1	1	1	0	0	0	2	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	7	0	0	0	0	11	0	8	0	0	0	20	2
VI	0	0	0	1	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	4	0	0	0	0	7	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	1	0	3	0	0	2	0	0	0	0	0	0	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	2	0	0	0	0	0	0	0	0	0	0
PM	0	1	0	9	0	0	0	0	0	0	0	0	0	0
PI	0	0	0	1	0	0	1	0	0	0	0	0	0	0

Table 8.26: Back imagery links for P-12

For other imagery links there were a total of 27 links across the design session, as seen in Table 8.27, including 13 VG to PI links. In total there were 13 types of links for the BRS stage, 12 for the GEN stage, 16 for the EVA stage and 12 for the DEV stage, with all networks found in Appendix 23. Shared network connections were found in VP to VG, VP to PM and PM to DVm.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	1	0
DVm	0	0	0	2	0	0	0	0	0	0	0	0	8	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	1	0	0	0	0	4	1	8	0	0	0	1	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	1	0
VS	0	0	0	1	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	0	0	0	0	0	2	0	0	0	1	1
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	1	0	3	0	0	4	0	0	0	0	0	2	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	2	0	0	0	0	0	0	0	0	4	0
PM	0	7	0	7	0	0	2	0	6	0	0	0	0	1
PI	0	0	0	13	0	0	5	0	0	0	0	0	4	0

Table 8.27: Other imagery links for P-12

Overall, for P-12's design process there were 188 imagery-action links over a total of 68 different concurrent link types. For the full design process there were 99 links categorised under PhA codes with 28 types, 26 PeA with 11 types, 22 FA with 12 types and 41 CA with 17 types. These included 12 VG:Ds-a, six VG:O-a, seven VG:V-a, and nine PM:K-a concurrent links. The full matrix can be found in Table 8.28, and a shared network connection was found between VG:Ds-a and PM:K-a.

There were 32 concurrent links total over 19 types of links for the BRS stage of the design process, which was broken down into 16 PhA links over six types, three PeA links over three types, two FA links over two types, and 11 CA links over eight types. The GEN stage contained 55 links total over 29 different types, with 29 links for PhA codes with 12 types, six for PeA codes with five types, six for FA codes with three types, and 14 for CA codes with

nine types. Following this there were 55 links total across 29 types of links for the EVA stage. These consisted of 29 PhA concurrent links across 15 types, two PeA links with only one type, 13 FA links across seven types, and 11 CA links across six types. Finally, there were 46 concurrent links for the DEV stage with 23 different types of links recorded. This included 25 PhA links across 11 types, 15 PeA links across eight types, only one FA link, and five CA links across three types, with the full networks found in Appendix 23.

Action	Imagery													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	0	0	0	0	0	0	0	0	0	0	0	4	0
Da	0	0	0	4	0	0	1	0	2	0	0	0	1	0
Ds	0	8	0	12	0	0	5	1	6	0	0	0	6	0
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	1	0	7	0	0	7	0	3	0	0	0	3	2
Lp	0	0	0	6	0	0	2	0	2	0	0	0	2	0
Lb	0	0	0	1	0	0	0	0	0	0	0	0	1	0
H	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Hd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hf	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hp	0	0	0	1	0	0	2	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mp	0	0	0	0	0	0	0	0	3	0	0	0	5	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	2	0	0	0	0	0	0	0	0	1	0
O	0	0	0	6	0	0	3	0	4	0	0	0	1	1
A	0	0	0	1	0	0	0	0	0	0	0	0	0	0
C	0	0	0	1	0	0	3	0	3	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	4	0	0	0	0	0	1	1	0	0	0	1	0
U	0	1	0	0	0	0	1	0	0	0	0	0	0	0
W	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V	0	1	0	7	0	0	1	0	1	0	0	0	2	0
E	0	0	0	0	0	0	0	0	0	0	0	0	1	0
G	0	1	0	4	0	0	0	0	1	0	0	0	1	0
K	0	1	0	1	0	0	0	0	0	0	0	0	9	1
I	0	0	0	1	0	0	0	0	2	0	0	0	2	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	1	0	4	0	0	6	0	3	0	0	0	2	0

Table 8.28: Concurrent links for P-12

8.6.10 Participant 13

Occurrence

P-13 logged a total of 332 segments across a design time of 29 minutes and 14 seconds and at an average of 5.30 seconds per segment for the entire design process. There were 65 total imagery codes, with an average of 0.20 per segment, and 518 action codes, at an average of 1.56 per segment. 20% of segments were coded with an imagery code, and 99.50% received at least one action code. All imagery codes had concurrent action codes, and only one code (0.50%) was left uncoded, with 80% of codes remaining as action only codes.

The BRS stage lasted five minutes and 52 seconds in length, with 72 segments and an average segment length of 4.90 seconds. The 20 imagery codes were allocated to 28% of all segments, with all codes receiving concurrent action codes. There was an average of 0.28 imagery and 1.58 action codes per segment, with 72% of segments receiving only action codes. There were no uncoded segments for any of the BRS, GEN or EVA stages, where all segments were allocated at least one action code. The GEN stage had 99 categorised segments over eight minutes and 46 seconds, with an average segment time of 5.30 seconds. There were 26 imagery and 152 action codes, with 26% of all segments allocated an imagery code. There was an average of 0.26 imagery and 1.54 action codes per segment for the GEN stage. The EVA stage was undertaken over a time of six minutes and six seconds with 77 total segments, seven imagery codes and 130 action codes. This calculated to approximately 4.80 seconds, 0.09 imagery codes and 1.69 action codes for each segment. Only 9% of segments were given an imagery code with 91% of segments receiving only action codes. Lastly, the DEV section was categorised into 84 segments over a time of eight minutes and 30 seconds, with an average time of 6.10 seconds per segment. There were 12 imagery codes and 122 action codes over the design stage, with 0.14 imagery and 1.45 action codes on average for each segment. 14% of all segments received an imagery code and 99% received at least one action code, with one segment (1%) remaining uncoded.

The imagery occurrence for P-13 over the whole design process was a sum total of 65 imagery codes, with an index of 47 new (72%), 18 continued (28%) and zero revised codes. There were 15 allocated Dx codes (23%, DVm only) which consisted of 13 new codes (87%) and two continued codes (13%). 45 codes were assigned to the Vx category at a total of 69%, with no VI, VS, VR, VF or VX subcodes utilised. There were 34 VG codes (76% of all Vx codes and 52% of all imagery codes), four VT codes (9% and 6% respectively) and seven VP codes (16% and 11%). The index for Vx codes was 29 new (64%) and 16 continued (36%). All Px categorised codes were assigned to the PM subcode and all indexed as new codes.

During the BRS stage, there were 20 total imagery codes assigned, with six Dx codes (30%, DVm only), nine Vx codes (45%, VG only), and five Px codes (25%, PM only). For the GEN stage, there were 26 total codes of which six were Dx category codes (23%, DVm only), 20 were Vx codes (77%) and none were Px coded. Of the Vx codes, 13 were VG codes, two were VT, and five were VP. There were seven imagery codes total for the EVA stage, with only one Dx code (14%, DVm), six for the Vx category (86%, VG only) and none for the Px

category. Lastly, there were 12 imagery codes for the DEV stage, with two for the Dx category (17%, DVm only) and ten for the Vx category (83%), with no Px codes logged. Six of the Vx codes were assigned VG and two each VT and VP codes.

P-13 logged a total of 518 action codes over their design process, with an index of 250 new codes (48%), 224 continued codes (43%) and 44 revised codes (9%). Of the 518, 374 were assigned to the PhA category (72%), 15 to the PeA category (3%), 74 to FA (14%) and 55 to CA (11%). The total of all cognitive-defined categories was 144 action codes and 28%. 194 of 374 PhA codes were assigned to D-a at 52% of all PhA codes and 38% of all action codes. A further 95 were assigned to L-a (25% and 18% respectively), 31 H-a (8% and 6%), 34 M-a (9% and 7%), one N-a (0.27% and 0.19%), and 19 X-a (5% and 4%).

There were no P-a or A-a codes assigned in the PeA category, while ten were logged as O-a (67% and 2%), and five as C-a (33% and 0.97%). For the FA category, 19 were assigned as F-a codes (26% and 4%), two as U-a (3% and 0.39%), 12 as V-a (16% and 2%), and 41 as W-a (55% and 8%). Finally, there were no E-a or I-a codes found within the CA category action codes assigned, while 34 were assigned G-a (62% and 7%), five as K-a (9% and 0.97%) and 16 as S-a (29% and 3%).

Links and networks

There were 13 total back link types for P-13 over their entire design process, with the full matrix found in Table 8.29 and including 14 VG to DVm links. Seven link types were found in the BRS stage, eight in the GEN stage, three in EVA and seven in the DEV stage, the full networks of which can be found in Appendix 24. Shared connection networks were found over the stages for VG to DVm and DVm to VG.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	1	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	14	0	0	0	0	0	0	0	0	0	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	13	0	0	0	0	2	0	7	0	0	0	4	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	0	0	4	0	0	0	0	0	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	2	0	8	0	0	0	0	0	0	0	0	1	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PM	0	0	0	5	0	0	2	0	0	0	0	0	0	0
PI	0	0	0	2	0	0	0	0	0	0	0	0	0	0

Table 8.29: Back imagery links for P-13

18 types of other links were found over the entire design session, including 15 VG to PM links, and the entire matrix of which can be found in Table 8.30. The BRS stage featured nine different link types, GEN ten types, EVA two types, and DEV seven types, with full networks found in Appendix 24. There was one shared network connection found for the other links, which consists of links between VG to PM.

Links	Imagery codes													
	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
DVv	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DVm	0	0	0	5	0	0	0	0	2	0	0	0	2	0
DVe	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VG	0	2	0	0	0	0	2	0	0	0	0	0	1	0
VI	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VT	0	2	0	0	0	0	0	0	0	0	0	0	0	0
VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VP	0	1	0	5	0	0	1	0	0	0	0	0	1	0
VF	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VX	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PP	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PM	0	8	0	15	0	0	1	0	2	0	0	0	0	0
PI	0	2	0	8	0	0	0	0	2	0	0	0	0	0

Table 8.30: Other imagery links for P-13

For the design process, there were a total 118 concurrent imagery-action links across 46 different link types and the full matrix is in Table 8.31. 69 of these were assigned PhA codes across 24 link types, including 25 VG:Ds-a links. A further nine were assigned PeA codes across six link types, including two DVm:O-a links, ten were assigned FA codes over seven link types with eight assigned DVm:F-a links and 33 assigned CA codes over nine links including eight VG:G-a links. There was a single shared network connection found between DVm:G-a.

During the BRS stage there was a total of 39 links found over 18 link types, with 20 allocated PhA codes over nine types, zero PeA codes, five FA codes over two types, and 14 CA codes over seven types. The GEN stage contained a total of 51 links across 25 link types. This included 26 PhA codes across ten types, seven PeA links across five types, six FA codes across five types, and 12 CA codes across five types. For the EVA stage there were no link types between either PeA codes or FA codes. Between the PhA codes and CA codes there were a total of 15 links over eight link types, with ten links for PhA codes at six link types and five for CA codes at two link types. Finally, there were 25 links found for the DEV stage across 15 link types, with 13 of these being for PhA codes across eight link types, two for PeA codes across two link types, eight for FA codes across four link types and two for CA codes with only one link type. All networks can be found in Appendix 24.

	Imagery													
Action	DVv	DVm	DVe	VG	VI	VS	VT	VR	VP	VF	VX	PP	PM	PI
D	0	4	0	1	0	0	0	0	0	0	0	0	0	0
Da	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ds	0	4	0	25	0	0	3	0	4	0	0	0	3	0
Dr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Db	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Lp	0	3	0	6	0	0	0	0	0	0	0	0	0	0
Lb	0	2	0	1	0	0	0	0	0	0	0	0	1	0
H	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Hd	0	1	0	1	0	0	0	0	0	0	0	0	0	0
Hf	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Hp	0	0	0	1	0	0	0	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mp	0	0	0	1	0	0	1	0	0	0	0	0	1	0
N	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ne	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Na	0	1	0	0	0	0	0	0	0	0	0	0	0	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O	0	2	0	2	0	0	1	0	2	0	0	0	0	0
A	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C	0	0	0	1	0	0	0	0	1	0	0	0	0	0
R	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F	0	2	0	9	0	0	2	0	0	0	0	0	0	0
U	0	0	0	1	0	0	0	0	0	0	0	0	0	0
W	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Wd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ws	0	0	0	1	0	0	1	0	2	0	0	0	0	0
V	0	0	0	0	0	0	0	0	0	0	0	0	0	0
E	0	0	0	0	0	0	0	0	0	0	0	0	0	0
G	0	7	0	8	0	0	0	0	0	0	0	0	1	0
K	0	0	0	2	0	0	0	0	0	0	0	0	1	0
I	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Id	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	0	4	0	7	0	0	0	0	1	0	0	0	2	0

Table 8.31: Concurrent links for P-13

8.6.11 Overall occurrence

Overall, the participants logged a total of 3,869 segments which calculated to an average of 4.30 seconds per segment. There were a total of 875 imagery codes logged by participants and 6,447 action codes. 23% of all segments received an imagery code, and 99% received at least one action code. Only one segment out of 3,869 was coded with imagery only at 0.03%, while 2,969 were coded with action only at 77%. Further, 880 were coded with both imagery and action codes at 23% and 19 remained uncoded at 0.49%. There was an average of 0.23 imagery codes and 1.67 action codes for any one segment.

For the BRS stage overall there were 698 logged segments with an average of 4.50 seconds, 0.29 imagery codes and 1.67 action codes per segment. 29% of segments were logged with an imagery code and 99.50% with an action code, while four segments (0.50%) were left uncoded. All imagery codes received a concurrent action code during the BRS stage. The GEN stage consisted of 1,162 total segments and an average of 4.30 seconds per segment. There were 290 imagery codes at an average of 0.25 per segment, and 1,947 action codes at an

average of 1.68 per segment. 25% of all segments received an imagery code with one receiving an imagery code alone (0.09%), while 289 imagery codes were matched with action codes (25%). 99.50% of segments were assigned action codes with four segments left uncoded at 0.50%. For the EVA stage there was an average of 4.00 seconds for each 902 segments, with 176 imagery and 1,522 action codes total. 20% of all segments contained imagery codes and 99.67% contained action codes, with an average of 0.20 imagery and 1.69 action codes per segment, and three codes (0.33%) left uncoded. For both EVA and DEV stages there were no segments coded with imagery alone and all imagery codes were given concurrent action codes. There were 1,107 segments total for the DEV stage with an average of 4.50 seconds, 0.19 imagery codes and 1.64 action codes per segment. There were 210 imagery codes and 1,813 action codes total with 19% of all segments assigned an imagery code and 99% assigned at least one action code. Eight codes remained uncoded at 1%.

For the overall imagery occurrence of all participants, there were 875 total imagery codes assigned throughout the entire design process of all ten participants. 565 of these codes were new codes at 65% and 310 continued codes at 35%, with no revised imagery codes for any participant during the study. 113 of the 875 codes were assigned to the Dx category at 13% with no DV or DVv codes logged for any participant. Of these 113, there were 109 DVm codes at 96% and four DVe codes at 4%, with 65 coded as new (57.50%) and 48 as continued (42.50%). There were 546 codes total for the Vx category (62%), with 65 coded as new (58%) and 48 as continued (42%). There were no codes assigned to the VS subcode for any participant. For the VG code there were 258 codes assigned at 47% of all Vx codes and 30% of all imagery codes, with six for VI (1% and 0.69% respectively), 138 for VT (25% and 16%), three for VR (0.55% and 0.34%), 135 for VP (25% and 15%), four for VF (0.73% and 0.46%), and two for VX (0.37% and 0.23%). Lastly, there were 216 codes for the Px category at 25% with 150 new codes indexed (70%) and 66 continued (30%). 34 codes were logged at PP (16% and 4%), 170 for PM (79% and 19%) and 12 PI (6% and 1%).

For the BRS stage there were 199 total imagery codes between all ten participants with 32 assigned Dx codes (16%), 105 Vx codes (53%) and 62 Px codes (31%). For the Dx category there were 31 assigned DVm codes and one assigned DVe. There were 58 VG codes assigned, 20 VT codes, one VR code and 26 VP codes. Two codes were assigned PP and 60 for PM with zero codes assigned PI in the BRS stage for any participant. During GEN there were 284 imagery codes total categorised across participants. 48 of these were assigned to the

Dx category at 17%, with 47 DVm codes and one DVe code. There were 185 Vx assigned codes (65%) with 98 VG codes, one VI code, 51 VT codes, 33 VP codes and two VF codes. Lastly, there were 51 Px codes at 18% with 12 of these being PP codes, 36 PM and three PI. The EVA stage contained 176 imagery codes total with seven Dx codes (4%, DVm only), 99 Vx codes (56%) and 70 Px codes (40%). The Vx codes consisted of 41 VG codes, five VI codes, 25 VT codes, 26 VP codes and two VX codes. The 70 Px codes were split into 19 PP codes, 43 PM codes and eight PI codes. Finally, for the DEV stage there were 216 imagery codes logged between the ten participants. 26 of these were Dx codes (12%) with a breakdown of 24 DVm codes and two DVe codes. There were 157 Vx codes (80%) which consisted of 61 VG codes, 42 VT codes, 50 VP codes and two each for VR and VF. A total of 33 Px codes were logged at 15% of all codes, with 31 PM codes and one each for PP and PI codes.

There was a total of 6,447 action codes across the entire design process for all ten participants. The index for these codes was 3,306 new codes (47%), 3,024 continued codes (47%) and 387 revised codes (6%). 4,866 of the total codes were PhA codes at 76% total. These were split into 1,960 D-a codes (40% of all PhA codes and 30% of all action codes), 1,185 L-a codes (24% and 18% respectively), 277 H-a codes (6% and 4%), 511 M-a codes (11% and 8%), 152 N-a codes (3% and 2%), 781 X-a codes (16% and 12%).

Overall, for all cognitive-defined codes there was 1,581 codes (25%) which consisted of 329 PeA codes (5%), 629 FA codes (10%) and 623 CA codes (10%). The PeA category codes were made up of 20 P-a codes (6% and 0.31%), 216 O-a codes (66% and 3%), five A-a codes (2% and 0.08%), and 88 C-a codes (27% and 1%). For the FA category there were 122 F-a codes (19% and 2%), 77 U-a codes (12% and 1%), 149 V-a codes (24% and 2%), and 281 W-a codes (45% and 4%). Finally, for the CA codes there was 36 E-a (6% and 0.56%), 210 G-a (34% and 3%), 90 K-a (14% and 1%), 76 I-a (12% and 1%), and 211 S-a (34% and 3%).

8.7 Summary

This chapter has detailed the data results of a study investigating the experience of visual imagery in the design process of 10 student designers. The study comprised of a questionnaire to explore the possibilities of developing a formal measurement system for mental imagery in engineering design, and a design session with follow-up interviews. The goal of the study is to map the entire design process of each participant, and analyse these by

participant, both for their overall process and by stage, with the interviews supporting the researcher's assumptions while coding and analysing the results. The results detailed here consist of all occurrence and link data for each participant, and for the overview of all participants together which have been calculated to provide averages as a means of comparison. The next chapter will present the participant maps of their design process and analyse the results. Each participant has been categorised into a profile based on their imagery actions. These profiles define the type of visualiser they are, and these will be detailed further in Chapter 9. Similarities and differences have also been uncovered that have allowed the development of Profiles of the Imaging Designer which allocate imagery and design markers of how a participant experiences their mental imagery during the design process.

Chapter 9: Profiles of Imaging Designers

9.1 Defining mental imagery in engineering design

As discussed in Chapter 8, this study aimed to demonstrate that diverse mental imagery experiences exist between engineering design students and throughout their individual design process. By mapping these experiences by participant and analysing the individual data, as well as performing some comparative analysis, profiles have been developed allowing greater insight on both individual and shared experiences of mental imagery in engineering design. These profiles will assist in developing a definition for the mental imagery experience in engineering design, as well as a shared language for future research. Using the data results from Chapter 8, this chapter will analyse the mapped experiences of each participant and detail the conclusions that have been drawn. The mapped sessions have enabled participants to be defined by their own individual imagery experience, as well as categorised into a profile based on shared experience and designer traits.

Analysis of the study was conducted on a mixed-methods basis, with quantitative data being investigated in the form of occurrence and link data, and qualitative research being undertaken on the individualities of each participant's manner of working. The individual data was analysed initially by comparing experience mappings between each of the ten participants to find individual experience markers, with each participant then being investigated individually both with and without action coding, as detailed throughout this chapter. The design processes revealed within the personal profiles are mapped according to timeline, with imagery and action codes mapped chronologically. To ensure full rigour, the process maps were also created with alphabetically ordered action codes. The results from this revealed that there were no noticeable improvements or differences when comparing the participants by ordered codes than by timing, with timing providing more granular detail in areas, such as by allowing investigation of how the participants begin a design section. Therefore, the alphabetically ordered maps have not been included for analysis and instead can be found in Appendix 25.

Following the analysis of the process maps, all link networks (Appendices 13-22) for participants were analysed for noticeable outcomes and similarities. This was followed by occurrence and link data analysis, with traits and notable differences highlighted throughout

to allow for common themes and individualities to be categorised. Inputting the qualitative data into a matrix enabled participant profiles to be developed in a simple and effective manner. The initial matrix, found in Figure 9.1, details imagery and action traits seen throughout the analysis stage as being key factors in how a participant works through their design process along the Y-axis, separated into those relating to their imagery experience, and those of their actions. Of these designer traits, those that were attributed to multiple of the participants have been assumed to be common trait similarities. Those categorised for only one of the ten participants have been allocated as unique markers of their design process as an individual. The quantitative occurrence and link data was then utilised to confirm the qualitative observations. This resulted in a new, expanded matrix, as seen in Figure 9.2. Emerging from the final matrix were three imagery and three action trait similarities, and ten individual participant profile markers. The individual participant traits are attributed to the designers as their “visualiser” style as follows:

- P-1: The Fixated Visualiser
- P-2: The Restless Visualiser
- P-3: The Silent Visualiser
- P-4: The Generating Visualiser
- P-5: The Intentional Visualiser
- P-7: The Inactive Visualiser
- P-8: The Unfocused Visualiser
- P-9: The Communicative Visualiser
- P-12: The Leisurely Visualiser
- P-13: The Focused Visualiser

The three imagery and three action traits have been categorised as the Profiles of Imaging Designers, with each designer allocated at least one imagery and one action trait each, as will be detailed further in this chapter. The imagery traits are as follows:

- The Clustered Imager
- The Evolving Imager
- The Unintentional Imager

The action traits can be seen below:

- The Active Designer
- The Conversational Designer
- The Hurried Designer

The profile of each imaging designer is made up of at least one trait from each category, for example, The Conversational Designer with Clustered Imagery, and will assist in defining the varying ways in which designers experience visual mental imagery in engineering design.

	P1	P2	P3	P4	P5	P7	P8	P9	P12	P13
<i>Active</i>	x	x	x	x	x					
<i>Inactive</i>							x			
<i>Quiet</i>		x	x	x						
<i>Talkative</i>								x	x	x
<i>Quick</i>			x			x	x			
<i>Slow</i>										x
<i>Focused</i>									x	
<i>Communicative</i>								x		

<i>Fixated imagery</i>	x									
<i>Evolving imagery</i>			x	x	x		x	x	x	x
<i>Early imagery</i>		x								
<i>Intentional imagery</i>					x					
<i>Unintentional imagery</i>			x							
<i>Decisive imagery</i>						x				
<i>Uncertain imagery</i>				x						
<i>Clustered imagery</i>		x		x	x	x		x	x	
<i>Consistant imagery</i>	x		x					x	x	

Figure 9.1: Version 1 of the Imagery Trait Matrix

	P1	P2	P3	P4	P5	P7	P8	P9	P12	P13
Active		x	x	x				x	x	x
Inactive						x				
Quiet			x							
Talkative	x						x	x	x	x
Quick		x	x	x	x	x	x	x		
Slow									x	x
Focused										x
Unfocused							x			
Communicative								x		
Uncommunicative										
Fixated	x									
Evolving					x	x	x	x	x	x
Early										
Late										
Intentional					x					
Unintentional		x	x			x	x		x	x
Decisive										
Uncertain										
Clustered	x			x	x	x		x	x	x
Consistent										
Generating				x						
Non-generating										
Fidgety		x								
Still										

Figure 9.2: Final version of the Imagery Trait Matrix

9.2 Participant imagery experiences

9.2.1 The Fixated Visualiser (P-1)

Considering the map of P-1's mental imagery experience across their entire design process (Figure 9.3), it is evident that mental imagery is not a constant consideration while they are working. The occurrence data detailed in Chapter 8 supports this, with only 38% of segments found to have been marked as imagery coded. It should be noted that this is not to say they are not consistently experiencing mental imagery; rather, their actions and verbalisations do not allow for additional assumptions to be made about their experiences. P-1's segmented data was assigned over four times as many action codes than imagery codes, with all imagery codes being allocated at least one concurrent action code, and no segments were coded imagery-alone. This indicates that all imagery experiences were occurring

alongside physical or cognitive actions, suggesting an inherent connection between the participant's mental imagery and their design process.

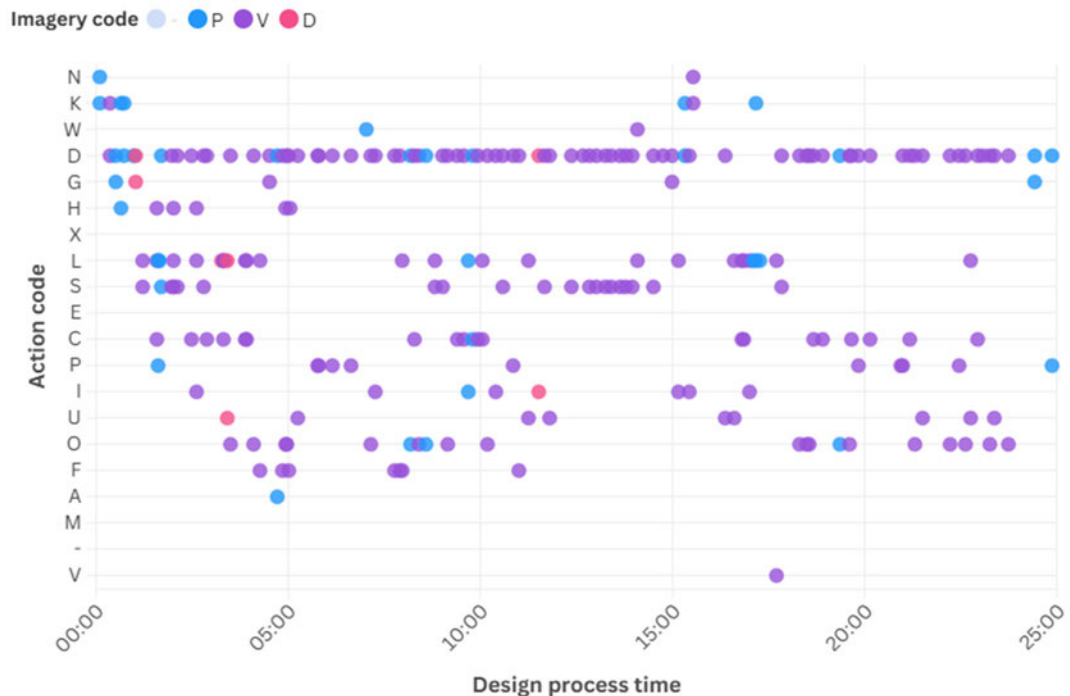


Figure 9.3: Imagery across the design process for P-1

While BRS, GEN and DEV all had similar times (seven minutes and one second, seven minutes and two seconds, and six minutes and 55 sections respectively) and total segments (94, 80 and 88 respectively), there were clear differences in mental imagery experience between stages of the design process. When considering the occurrence data detailed in Chapter 8, there is consistently sporadic imagery use throughout, and BRS returned 40 imagery and 153 action codes, while DEV returned 26 imagery and 123 action, suggesting there was more design occurring at the start of the process. The average time per segment across the entire design process was 4.80 seconds, with BRS featuring the fastest average at 4.50 seconds and GEN the slowest at 5.30 seconds. This provides evidence for more occurring at the start of the design process, since all stages have similar segment speed, and implying that P-1 was not necessarily spending longer on elements later in the process.

Despite BRS and GEN sharing similar percentages between action only and imagery-action codes at 57% and 43% for BRS and 54% and 46% for GEN, GEN has a clear highest experience of imagery with 46% of all segments assigned an imagery code, and an average

number of imagery codes per segment at 0.46. As a counter to this, DEV has the lowest experience of imagery at only 30%. Considering the map in Figure 9.3, imagery and action both appear to slow down across the design process, which is supported by the occurrence data in Chapter 8. DEV is also the only stage to feature uncoded segments with a total of three, suggesting that focus could be starting to decline towards the end of the session.

When looking at the imagery coding specifically, it appears that the mental imagery experience is clustered but consistent, as seen throughout the map in Figure 9.3. Also evident from the map is that the mental imagery experience of P-1 is visuospatial heavy, supported by the data which reveals Vx at 79% of all imagery codes. Additionally, P-1's reported experience of Dx was extremely low at only four codes and 3% of all imagery codes. This is clear from the map and with P-1's reported VVIQ result being that of high-level imagery vividness, it leads to questioning if this is connected.

Despite appearing consistent on the map (Figure 9.3), the data per stage reveals slightly different results than expected: Vx is continuous throughout (from 70% for BRS to 89% for DEV), but Px appears to reduce in later stages on the map. However, the data reveals this as untrue, with Px returning continuous results. BRS had the highest number of imagery codes, while GEN returned the highest average number of imagery codes per segment at 1.69, suggesting GEN has the highest average imagery across the stages. Alternatively, EVA returned the lowest number of imagery codes at 18 but also the shortest time, while DEV has the lowest average imagery codes per segment at 0.30, drawing the conclusion that imagery is occurring less during later stages.

There were significantly lower numbers of cognitive actions undertaken by P-1 than physical actions at 30% and 70% respectively, indicating an active design process. FA was the lowest coded cognitive action at only 6%, despite the GEN, EVA and DEV stages all starting with W-a codes, highlighting a more literal interpretation to the think-aloud method, and a low focus on functional actions overall. Further, D-a accounts for almost half of all actions at 43% and over 60% of all PhA codes, signifying a high level of physical design during P-1's design process. P-1 also had a very low amount of silence at only 8% of actions.

P-1's data included 27 types of back links, suggesting a more varied imagery use within each code. The "dependent on" or "back" codes indicate imagery taking place that cannot be assumed from the participant's actions or verbalisations alone, but that can be

construed is happening based on interview responses and further actions. This includes nine links with PI, which is largely unseen in the initial coding, highlighting the difficulty of inferring PI directly. BRS has the highest number of link types with 19, while DEV has the lowest, further supporting the conclusion that less imagery is occurring later in P-1's design process. With the "other" or "linked to" codes, this considers linked imagery occurrences that are challenging to judge subjectively, with P-1 assigned 30 different types of other links. These again include 35 PI links, and with DEV returning the lowest number, again, at only 11 links.

For concurrent imagery-action links, PhA codes are the most commonly linked with 122 total and the highest number of links per stage. The map in Figure 9.3 depicts a lot of imagery while sketching, which is supported by the total number of 85 links of imagery with Ds-a codes. There were only nine types of PhA links in GEN and five in DEV, both stages with higher levels of D-a coding, suggesting that while there are more design steps being undertaken, there are more codes of the same type of action. Also of note is that DEV's PhA codes were so low that it is the only stage of have more PeA link types than PhA and with minimal focus on concept or function actions within their imagery experience.

While P-1 had no reported or linked VX codes, based on the qualitative interpretation of the design work through their verbalisations and actions, they are a clear **Fixated** Visualiser. P-1 selected the treadmill idea approximately one minute and 36 seconds into their design time, and from that stage only worked to develop this concept, rather than generate any additional concepts. This is evident in the sketches in Figure 9.4, where minimal design changes can be identified. Further evidence of P-1 being a Fixated Visualiser are that they made clear early on they were utilising experience gained from discussions with a colleague, with the first utterance being "It's very similar to the individual project on of my friends is doing", referring to a colleague's University project. Additionally, with only one clear decision (V-a) undertaken and a very low focus on the solution (S-a, 5%), P-1's visualisation and design process being fixated on their initial concept is justified.

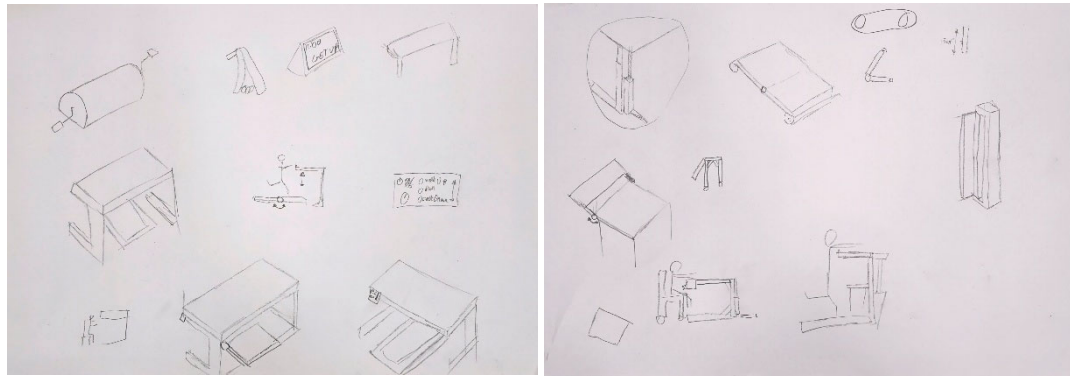


Figure 9.4: Design outputs during BRS and DEV respectively for P-1

9.2.2 The Restless Visualiser (P-2)

With only 18% of P-2's segments imagery coded, it is evident that the participant either has a very low level of imagery during their design process, or a significantly larger focus on action during the design session. Over 89% of all codes are action codes, with only four segments left uncoded overall, indicating almost constant physical or cognitive activity. Despite a slow start of 5.60 seconds per segment, P-2 had a quick overall time with 4.07 seconds per segment average, and with EVA stage being the fastest at 3.50 seconds. When considering occurrence levels by stage, BRS undoubtedly has less activity and longer segments, with the most uncoded segments at three (5%), but the highest percentage of imagery-coded segments. Counter to this, the EVA stage has the fastest segment time but the lowest percentage of imagery-coded segments, with over 14 times as many action codes than imagery codes, suggesting faster design actions with a lower imagery experience.

P-2's data was coded with Dx and Px the exact same number of times, with a much higher occurrence of Vx codes. Overall, VG was the highest Vx subcode, with VT and VP returning even totals, and there is some small evidence of fixation with two occurrences of VX codes. With a much higher index of new activity, P-2's design process is quick-changing, with qualitative feedback noting that their design process appears scattered and restless to watch.

Overall, all stages of P-2's design process returned very low imagery codes with only 20, 20, 12 and 25 respectively for BRS, GEN, EVA and DEV. There are very little variations in subcodes for Vx overall, but with the totals per stage running so low it is difficult to conclude on meanings behind these figures. GEN has the lowest variety of all stages with the only

subcodes assigned being VG, PP, PM and DVm. Further, EVA has no Px codes assigned and the highest level of VX codes at two, with no obvious imagery occurring for over two minutes at one point during the stage. Both EVA and DEV also have minimal to no Dx or Px codes, supporting the conclusion that there is less imagery occurring later in P-2's design process.

The map in Figure 9.5 depicts more physical activity at the start, with the process immediately beginning with a focus on the brief and the participant's knowledge. Additionally, a lot of hand gestures occur without any imagery at 4% of action codes, or 30 codes, compared to only two with imagery. It can be inferred from this that either P-2 is utilising hand gestures without imagery, or the imagery is occurring before or after the hand gesture itself. P-2 also exhibits a higher level of silence later in the design process, as can be seen in the map in Figure 9.6. From the occurrence data in Chapter 8, there is a drastically higher level of PhA than cognitive activity throughout the process with a difference of 78% to 22% indicating an active design process. There are also a high level of revised Ds-a codes, with over half of all revised codes assigned to Ds-a, which reveals a repeated return to previous sketches and changes being made throughout the process.

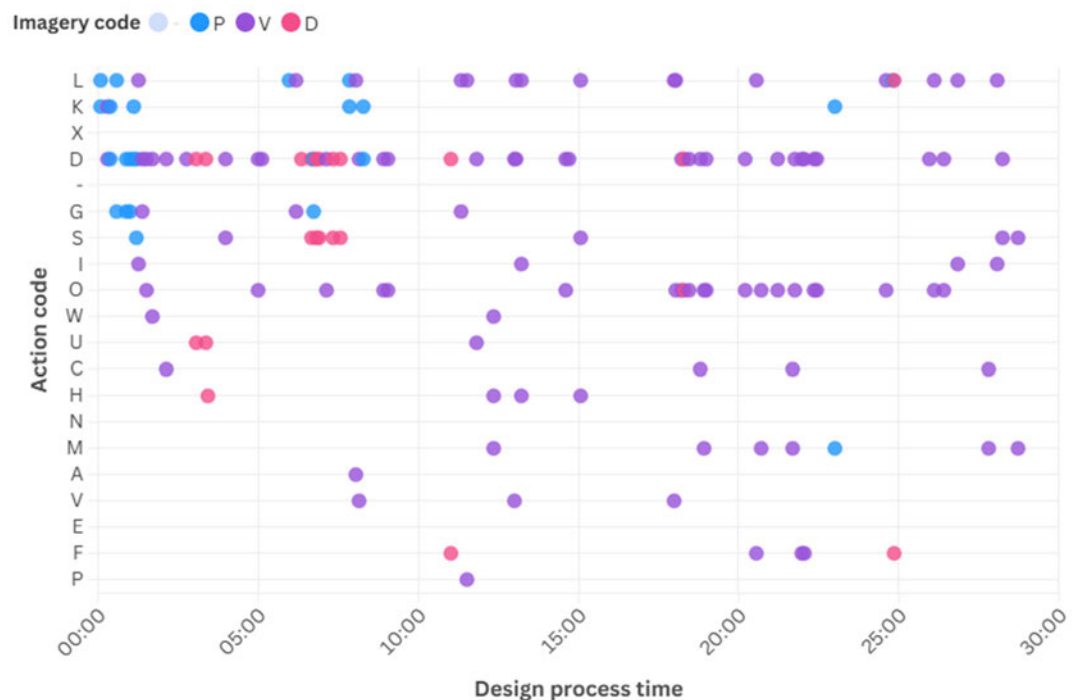


Figure 9.5: Imagery across the design process for P-2

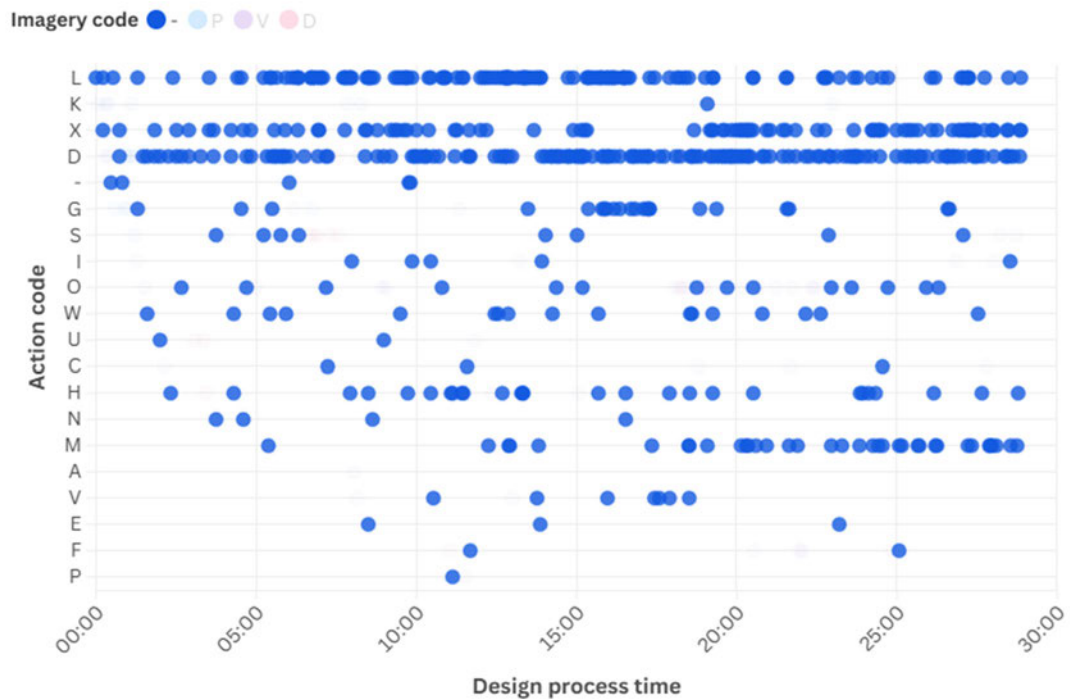


Figure 9.6: Action without imagery across the design process for P-2

There were 19 types of back links, but only one PI link so the assumption of imagination imagery happening without realisation is less clear cut for P-2. The highest number of back links was only 11 for DVm to VG, with higher types of links at the start and end. Despite this, there were low numbers of back links overall which indicates a lower imagery experience. The other imagery links were more varied suggesting there may be more unintentional imagery going on within P-2's mind that they are unaware of. At 149 links total and 60 types, the total for imagery-action links is high throughout, with the most links found with PhA codes, as expected from the maps in Figure 9.5. However, the low link and type numbers when compared to overall action occurrence indicates a large portion of action happening without clear imagery. With P-2 reporting a high-level imagery vividness in the VVIQ and confirmation in interviews that they are visualising as assumed, it does lead to questions being raised about their understanding of mental imagery and visualisation, and if the apparent discrepancy could be connected to a miscommunication of definitions, meaning and shared language.

9.2.3 The Silent Visualiser (P-3)

P-3 had a clear low level of mental imagery across their design process, as evident in the map in Figure 9.7, and in their occurrence data, with only 18% of segments imagery coded. There were over 89% more action codes logged than imagery codes and over 4/5 of all segments contained action codes. One standout data point to note is that P-3 is the only participant to log an imagery-only segment which occurred during the GEN stage of the process. Overall, P-3 worked quickly with an average of 3.50 seconds per segment, the fastest stage being during EVA with only 3.00 seconds average per segment. GEN is the busiest stage by segments and code numbers, with the highest number of imagery codes of all stages, indicating the most design occurrence at this stage.

While Px imagery appears lower in map analysis, seen in Figure 9.7, the Dx occurrence is significantly lower, with a higher Vx occurrence. The maps reveal consistently low imagery, supported by the low occurrence data detailed in Chapter 8. The highest Vx code occurrence is for VG, and there is a notable one mention of form (VF) in P-3's data. P-3's process was assigned no PP codes highlighting limited to no awareness of imagery use, or a very unintentional imagery experience. Given that P-3 responded to intention questions that they were aware of their imagery use during their design process, it can be assumed that there is a higher likelihood that they are unintentionally experiencing mental imagery. Further, P-3 logged 73% of imagery codes as new codes, which, when compared to their high VG response, suggests they generate a lot of new images in design. By stage, the imagery occurrence totals differ slightly with BRS containing only codes VG, VT and PM but the second highest number of imagery codes, indicating a potentially condensed mental imagery experience. EVA had a relatively even mention of PM and PI, which is different than other stages and participants with little PI mention, but given the numbers are only three and four codes respectively, it is hard to draw concise conclusions on this data. The DEV stage, as well as containing the least amount of coded imagery, only contains VG codes and one VF code, presenting an unvaried experience of mental imagery during concept development.

There was a much higher occurrence of PhA than cognitive actions in P-3's design process, at a difference of 81% PhA codes to 19% cognitive codes, indicating an active design process. All PhA coded actions had occurred before any cognitive actions, as per the map in Figure 9.7. Also evident in the map in Figure 9.7 is the significantly low level of PeA codes at only 3% of all action codes, suggesting minimal focus on perceptual cognition elements, with

the only PeA code being O-a. Almost one fifth of P-3's total action codes were recorded as silent periods inferring they were silent for almost 20% of the design session and spent large periods of their design time working internally, despite instructions to do the opposite. Lastly, of the 50 revised action codes logged, the majority of these were D-a codes, and represented a consistent return to previous sketches and notes.

With only 18 back link types, the highest being 14 links for PM to VG, and 15 other link types, the highest being 18 for VG to PM, it can be inferred that P-3's mental imagery experience over their design process is, in fact, low overall. With a small number of linked imagery experiences, it is hard to deduce anything other than there is no additional imagery occurring that the participant is unaware of. Additionally, P-3 logged a low number of concurrent imagery-action links, with only 110 links over 41 types. PeA and FA links were significantly lower, with a higher number of CA linked actions at 39 over eight. Of note, there was a large number of S-a links with imagery at 22 total, which suggests an unintentional imagery focus on the design solution. Overall, there is a significant lack of imagery apparent in P-3's design process, which is surprising given they reported a high level of mental imagery vividness in the VVIQ, but with their silence throughout, it is proposed that two potential reasons are a lack of motivation or a personality conflict with the think-aloud method in that they may be uncomfortable with verbalising their design process.

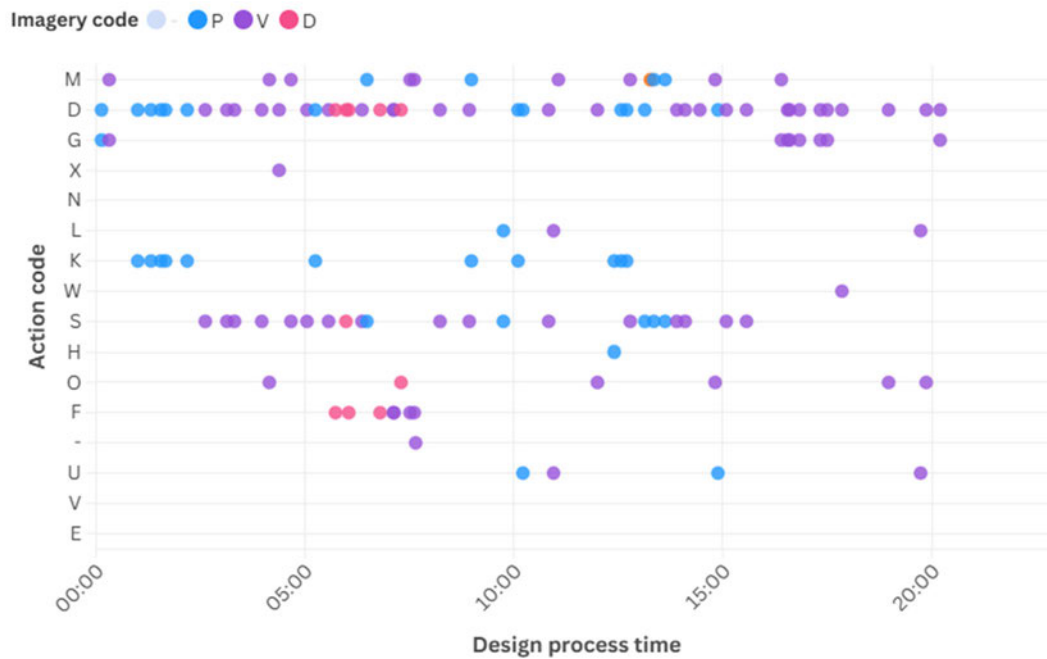


Figure 9.7: Imagery across the design process for P-3

9.2.4 The Generating Visualiser (P-4)

Overall, P-4's design time was quick paced with a total average of 4.00 seconds per segment of design work, but with minimal consistency when considering EVA at 3.20 seconds and DEV at 4.50 seconds per segment, indicating slightly varying speeds throughout the process. 20% of all segments were coded with imagery which calculates to approximately one fifth of all segments. There were almost eight times as many action codes logged than imagery codes, presenting a very active design session from P-4. Considering the total codes logged, segments and design times, it is evident that higher occurrences are distributed evenly around higher timings, so comparisons should be made between average segment times and code numbers, all of which are relatively even between stages.

Of the occurrence imagery totals, Vx appeared most frequently, while Px occurred least frequently, both of which is evident in the map in Figure 9.8. Almost half of the Vx codes are logged VG indicating very generative imagery for P-4, and there was a single inclusion of VI imagery. Further, only one PP code was logged with Px consisting predominately of PM codes. When analysing the map in Figure 9.8, there are clear clusters of imagery throughout, indicating that P-4's imagery is not constant and instead clusters in periods throughout their

design process. Dx occurrence was significantly higher during the BRS and GEN stages by percentage, which could be connected to P-4's reported hyperphantasia level mental imagery vividness. VG codes are higher in BRS, where VG is the only subcode for Vx, and in EVA, where VG is the only assigned code at all, adding further evidence to P-4 experiencing very generative mental imagery during their design process.

There was a much higher occurrence of PhA codes at 79% versus 21% for cognitive-defined categories. This is both clear from the map in Figure 9.8, and from watching P-4's design process both during the study and through the recordings: they work in a very active manner with almost constant movement. 173 cognitive codes is a high number, but the sheer volume of 644 PhA codes drastically reduces the percentage. Over 16% of the action codes are for silence and over 40% of all PhA codes are D-a logged, with barely any H-a logged codes suggesting a low level of communication on P-4's part. As per the map, Figure 9.8, there are more H-a codes towards the end, indicating a slight rise in communication, while still being low overall.

There were a high number of back link types for P-4 with 24 total, and up to 14 per any link type, including for VT to VG and VG to PM. This suggests a high level of background imagery that is potentially not obvious to the participant. There are a further 27 links in the other category across all stages with the highest 16 for GEN and 15 for DEV, indicating a more in-depth imagery experience than is apparent from verbalisations and actions, and highlighting the issue with the lack of objective measurement options for mental imagery research. There were 198 total concurrent imagery-action codes across P-4's design process, which is a very high total, but only 55 types revealing a more condensed mental imagery experience when it comes to the participant's action during the design process.

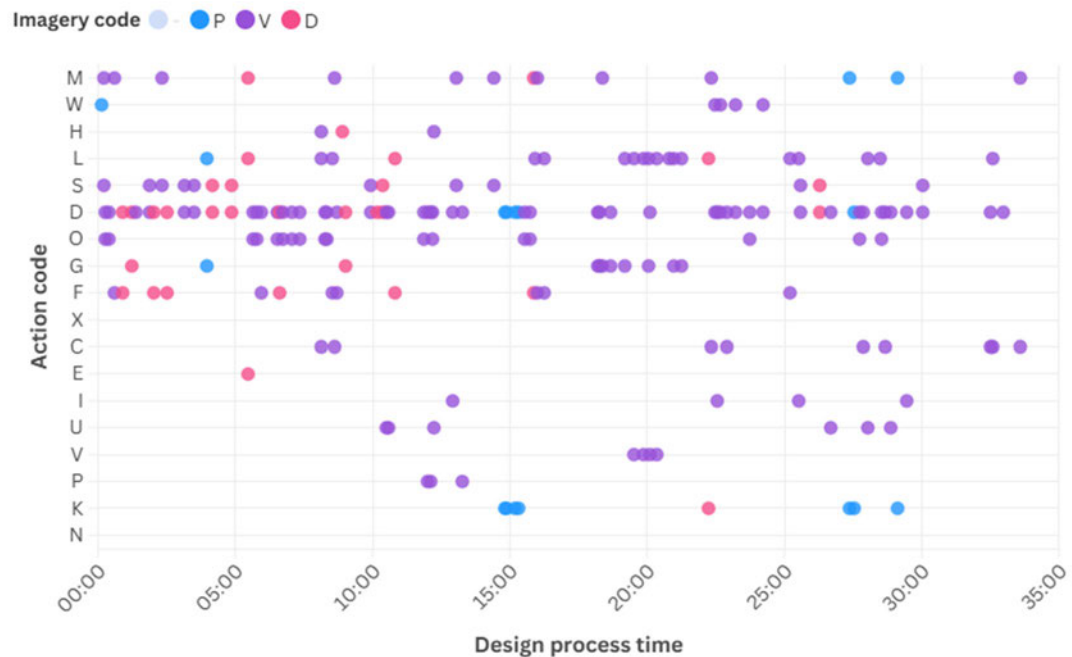


Figure 9.8: Imagery across the design process for P-4

9.2.5 The Intentional Visualiser (P-5)

Despite P-5 talking directly about their imagery regularly throughout the design session, they were intentionally imaging less than one fifth of the time, with over nine times as many action codes logged as imagery. Additionally, there were over four times as many action-only segments as those with imagery. As can be seen in the map in Figure 9.9, there was a significant time jump of almost ten seconds at the start of the design session before P-5 began discussing their imagery. The overall average time per segment for P-5 was 4.30 seconds, with the slowest segment time during BRS at 5.30 seconds and the fastest at the end with 3.80 seconds, suggesting more design activity was occurring and at a quicker pace at the end of the design process than at the start. Despite this, less imagery was occurring at the end of the process with only 10% of segments during DEV coded with imagery, compared to 28% during BRS indicating changing imagery throughout. Further, there was an average of only 0.10 imagery codes per segment at the end of the design process, and from the map, P-5's mental imagery appears to be clustered during this period.

There were only four occurrences of Dx codes across the entire design process for P-5 at 4% total, compared with 48.50% of Vx and 47.50% of Px. It is worth querying whether

P-5's high level reported imagery vividness in the VVIQ impacts on their consideration of mental imagery vividness. The Vx subcodes reported for P-5 are varied, along with the Px subcodes, with more PP and PI occurrences than other participants. PP was significantly higher than expected but from the qualitative analysis, it is evident that P-5 was directly discussing their imagery, revealing a higher awareness of their own internal experience. For the EVA stage, the only category coded was Px, with 86% coded at PP. From the qualitative data, P-5 was clearly actively aware of their imagery and utilising it to visualise their evaluative process in particular.

Over three quarters of the action codes were logged in the PhA category, with only 23% cognitive. However, less than a quarter of the time was spent depicting, suggesting a less active design process, despite the emphasis on physical actions. Over 15% of P-5's design process was assigned a silence code accounting for some of the higher level of physical actions. Further, 8% of all action codes were logged as a W-a code which reveals a literal interpretation of the think-aloud method.

There were 20 total back link types and 28 other link types for P-5's imagery coding. The EVA stage revealed significantly lower back and other links than other stages which suggests lower imagery experience here, despite the participant's apparent awareness of it. This indicates that since the participant is aware of their imagery, less is going on without them knowing and there is a lower overall experience of imagery during this stage. There were a further 189 concurrent imagery-action links across 55 types, with PeA links particularly low at only 18 over five types. Despite this, the data was overall varied with concurrent links, the highest of which was 80 over 42 during the GEN stage, allowing the conclusion that there were more varied imagery-actions during this stage, and a vaster experience of mental imagery.

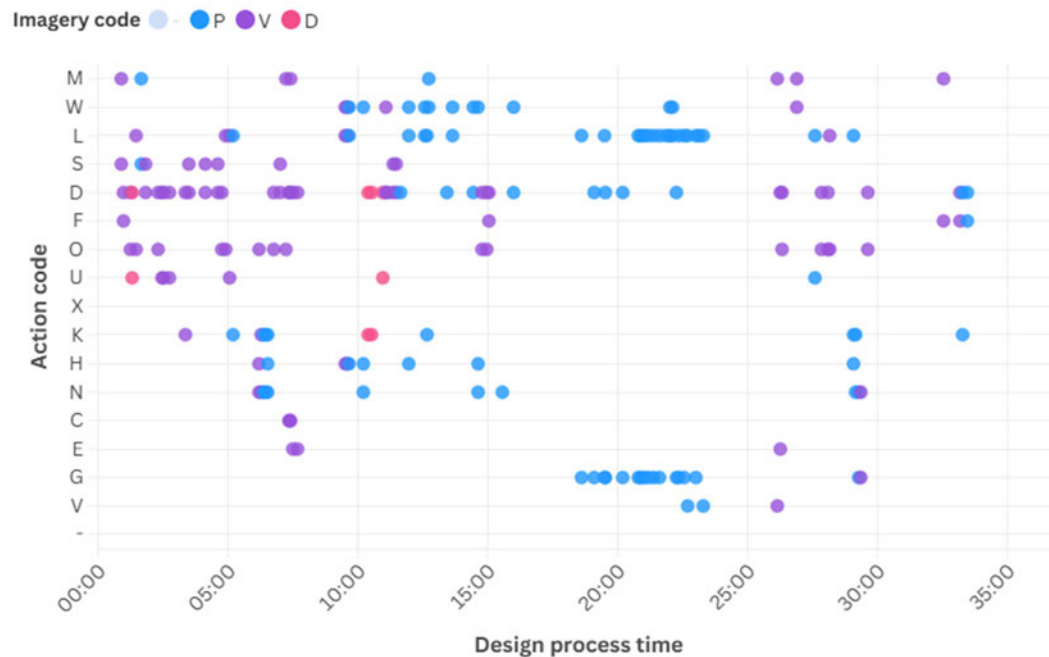


Figure 9.9: Imagery across the design process for P-5

9.2.6 The Inactive Visualiser (P-7)

While P-7's average design time per segment was approximately average at 4.40 seconds, the total design process time of 22 minutes and 35 seconds is a very short overall time. Of the total 308 segments, approximately one quarter were coded as imagery which is significantly higher than was assumed during the map analysis (Figure 9.10). Despite this, P-7 logged more than seven times as many action codes to imagery codes. Segment times were similar across all stages, but with an extremely low design time for DEV of only three minutes and 35 seconds, the reason for which is unclear but could signify either a point of fixation or a lack of commitment from the participant. The highest percentage of imagery and highest number of imagery codes per segment were for EVA with 41% and 0.41 respectively, while the lowest was for DEV with 10% and 0.10 respectively. This indicates a lower experience of imagery across the DEV stage, with more focus on finalising the outcome.

Almost half of all imagery codes were logged as Px codes at 46% but with no PP codes suggesting unintentional imagery use throughout the process. 80% of all Vx codes were subcoded as VG and 87% of all imagery codes were new codes. It was noted during the study that P-7's imagery and actions appeared random which may be supported by the volume of

new codes and the speed at which P-7 is moving through imagery segments. From the map in Figure 9.10, the imagery experience of P-7 is clearly evolving and clustered throughout the design process. The imagery in each stage lacks variety, with BRS containing only VG and PM codes, GEN more imagery but mostly VG codes, no Dx codes at all after GEN and only PM codes in EVA. Further, DEV contains only five imagery codes total which is a significant drop in the number of codes featured, even after considering the short design time.

There were minimal observations of note from P-7's action occurrence totals, with over three quarters logged as PhA codes and only 22% as cognitive-defined codes. There was a silent period at the start of the process, as seen in Figure 9.10, and P-7 was silent for almost 20% of the total time. P-7's total combination of active action codes (D-a, L-a, H-a and M-a) was calculated at 48% of all action codes, which is the lowest of all participants and signifies an inactive participant.

P-7's design activity featured only 13 types of back links and 14 types of other links total across all stages of the design process. The low number of imagery links when combined with the low imagery experience verbalised suggests a low experience of mental imagery overall. From the moderate-level VVIQ score reported and the interview responses of the participant, it is possible to conclude that P-7's experience of mental imagery in the design process is, in fact, low and that they do not rely as heavily on their internal images as other designers. There were 152 imagery-action links overall but with only 34 types which reveals a lack of variety in the types of actions undertaken alongside imagery. BRS stands out with only 28 links across nine types, none for PeA and only one for FA. Further, there were only two link types for EVA with only D-a and V-a codes, clearly indicating the high focus on decision making and noting said decisions alongside mental imagery.

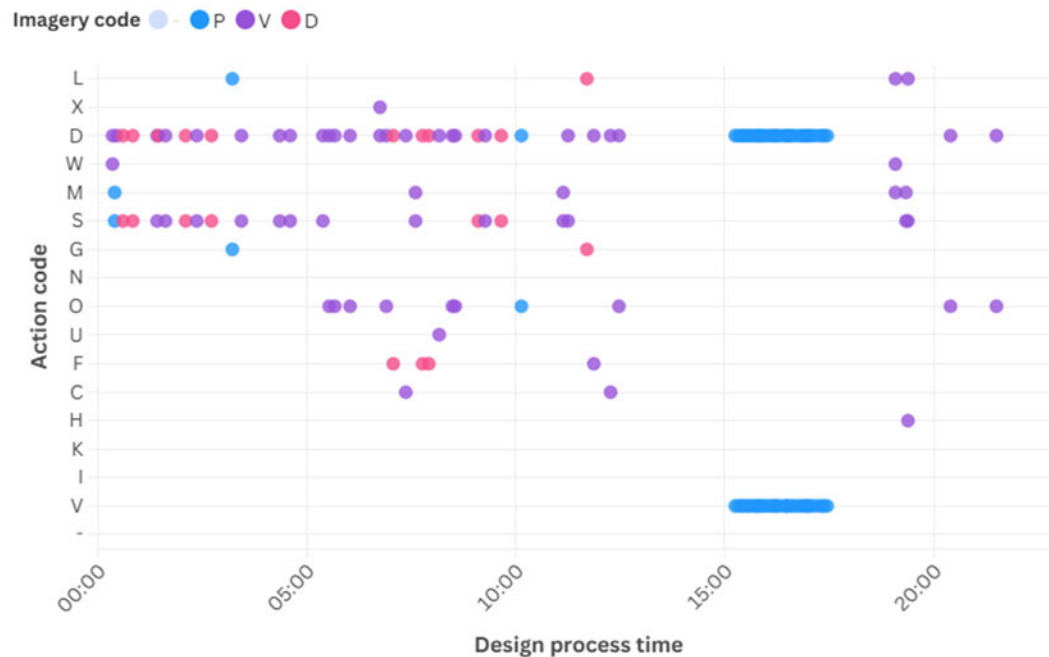


Figure 9.10: Imagery across the design process for P-7

9.2.7 The Unfocused Visualiser (P-8)

With less than 20% of segments imagery coded and over nine times as many action codes than imagery codes, P-8's imagery experience appears low, which is surprising considering their reported high level mental imagery vividness in the VVIQ. Overall, P-8 had a very low design time of less than 20 minutes total, with an average of 3.40 seconds per segment. Each stage undertaken was completed in less time than the limit set by at least one minute and 19 seconds, with the average per segment for each stage ranging from as low as 2.70 (EVA) to 4.40 (DEV). The fast segment times indicate quick-paced designing and fast-moving mental imagery when it does occur. BRS contains the highest imagery occurrence at 31% with all other stages remaining under 20%. EVA is the only stage with no uncoded segments suggesting more targeted actions during the evaluation portion of the design process. The map analysis, Figure 9.11, reveal clearly changing mental imagery over the course of the design process, as well as a large imagery gap at the end of the session. When considering the segmented data qualitatively, it is evident that the participant is focused more on dictating what they are doing action-wise, for example through their sketch, than verbalising what they are thinking.

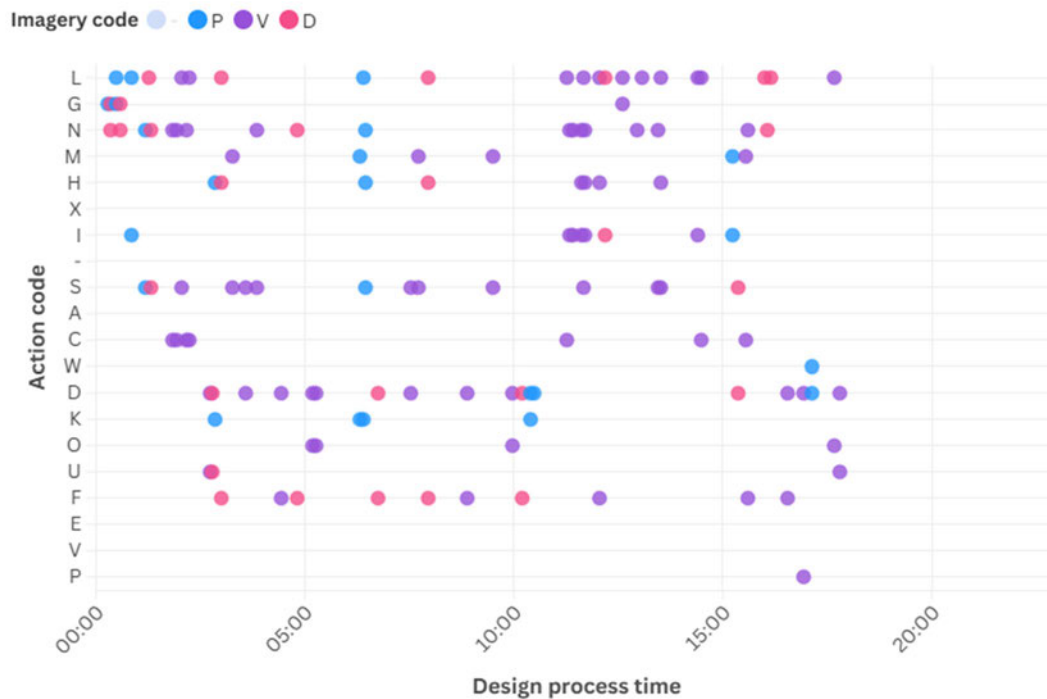


Figure 9.11: Imagery across the design process for P-8

When considering the map in Figure 9.11, the data looks significantly less distributed but the occurrence data detailed in Chapter 8 produces a different result, with the visuospatial category occurring significantly higher than others at 58%. Despite this, the Vx subcodes are not varied but do depict a larger focus on spatial imagery (VP) at 49% of all codes. The BRS stage returned remarkably low mental imagery numbers and no VG-imagery at all which is surprising given that the participant worked entirely in their mind during this portion of the session, with no depictions and very minimal PhA during this time. Further, 93% of all EVA imagery is Vx coded with only one DVm code aside from this, and 60% of the Vx codes are for VP imagery indicating a new focus for evaluation. Lastly, there are barely any imagery codes logged for DEV with only 12 total and no generation at all, allowing the conclusion that P-8's mental imagery slows to negligible amounts by the end of the design process.

For action occurrence, the maps in Figures 9.11 and 9.12 depict very physical coding at the start of the design process, with the exception of D-a codes. There were slightly higher levels of cognitive actions than some other participants with almost one quarter of action codes cognitive compared with three quarters PhA. Less than 20% of action codes were for depictions and there were no depictions at all before the GEN stage, with the entire BRS stage

being undertaken solely in the participant's mind. 9% of action codes were assigned as N-a codes which is high and indicates a much lower focus within the design space.

There were only 18 types of back links and 20 types of other links total during P-8's design process, which is low overall, and with no standout individualities in stages. This suggests that there is a limited amount of unseen mental imagery occurring for P-8. With the concurrent imagery-action links there are 127 links total over 54 types, with the lower levels of links over a higher number of types inferring a less condensed level of mental imagery across the action links. The highest level of links and types across all stages, except DEV, is CA revealing a higher focus of conceptual actions with imagery.

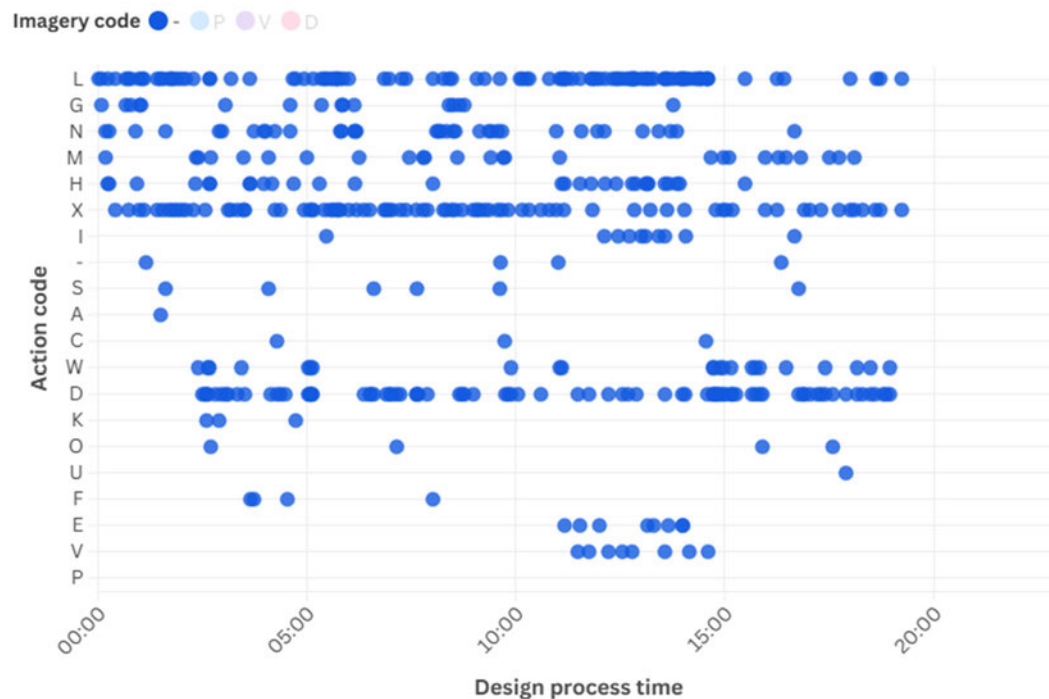


Figure 9.12: Action without imagery across the design process for P-8

9.2.8 The Communicative Visualiser (P-9)

P-9's design process was fast paced with an overall average segment time of 3.90 seconds, and a slowest segment time of only 4.10 seconds (DEV). With almost 30% of segments imagery coded, P-9's mental imagery experience appears as high, which is surprising given their low-level report of imagery during the VVIQ. It is possible that P-9 is more aware

of their mental imagery experience as it is not as naturally occurring as other participants. There are over six times as many action codes than imagery which is fairly low when considering the other participants, and there appear to be a large number of concurrent imagery-action codes with an average of 0.29 imagery and 1.79 action codes per segment. The BRS, GEN and EVA stages all have strikingly similar total design times and segment numbers at five minutes and six seconds, five minutes and five seconds, and five minutes and two seconds, and 80, 85 and 80 segments respectively. DEV is the exception to these similarities with a slower segment time of 4.10 seconds and a longer overall design time. As can be seen in the map in Figure 9.13, P-9's imagery evolves over the design process with different experiences during each stage.

The imagery occurrence totals for P-9 are visuospatial heavy at 52% but with Vx subcodes much more varied than previous participants with only VS and VX missing. There are a significant lack of PP and PI codes, which is clear in the map (Figure 9.13) and suggests an unintentional imagery experience. Px is considerably higher during BRS with over 85% of all imagery codes logged as Px and all subcodes being PM, indicating a high level of memory imagery during BRS. As the map reveals (Figure 9.13), EVA has the lowest level of imagery than all stages suggesting P-9 is evaluating with actions rather than imagery. Further, DEV has a large jump up to 49 imagery codes, with a large amount of variation in Vx, leading to the conclusion that imagery experience is higher towards the end of the process for P-9.

Almost 30% of P-9's action codes are for cognitive defined codes versus approximately 70% for PhA. P-9's D-a, L-a, H-a and M-a codes total 65% of all codes which infers a very high level of activity over the design process. Further, only 3% of the action codes are X-a which reveals a very high level of verbalisation throughout the session. This low level of X-a combined with a high level of H-a codes presents P-9 as a communicative visualiser who utilises different methods to communicate their ideas. P-9 also focused approximately 7% of the time on function and user, both of which were backed as important considerations by the participant during the interview portions of the session.

There was a total of 21 back and 29 other links for P-9's design process which reveals variation in types of links. The DEV back links are particularly high with 47 across 15 types, although with no P-links, while BRS has only four types of back links. This implies further that there is increasing and evolving imagery use during the design process. P-9 has an extremely high number of concurrent links at 241 total over 86 types which is much higher

than other participants. There are 146 PhA links alone with 50 types, revealing a large amount of variation in the concurrent imagery-action links. BRS is an exception with only 35 links and 16 types, and there are significantly fewer PeA links than other categories across most codes, with the DEV stage containing the most varied imagery-action links of all stages.

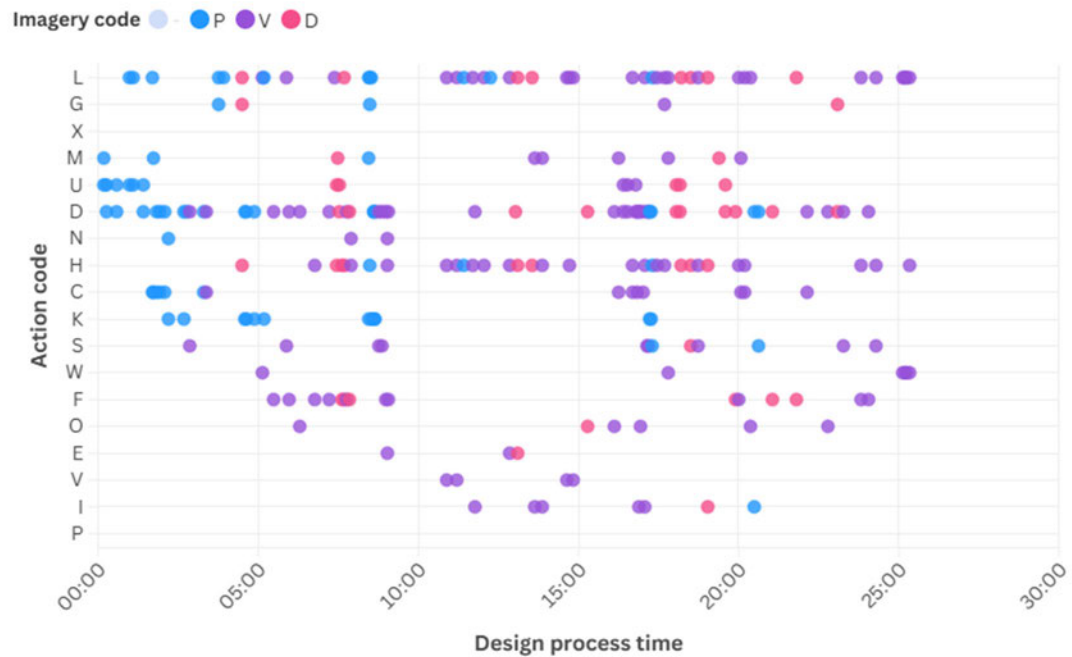


Figure 9.13: Imagery across the design process for P-9

9.2.9 The Leisurely Visualiser (P-12)

The most notable element of P-12's design process is the long segment times and long overall design time at over 37 minutes in total length. P-12's overall segment average is 5.70 seconds with a range from 5.30 (EVA) to 6.60 (BRS). As per P-12's qualitative feedback, the participant is not necessarily verbalising or doing more during each segment, rather there are periods of pause within the segments. While it is important to note that P-13 also returned slow segment times, P-12 was attributed as a "leisurely" designer due to a combination of the slower times and their qualitative feedback being that they appeared to have more fun with the task than any other participant and gave a laidback impression of their design process.

P-12 was assigned 24% imagery codes overall for their segments with almost six times as many action codes than imagery codes but given their long design time of over 35 minutes,

398 segments is a low total. Combined with their slow segment times, it supports the conclusion that they worked through their design process in a more laidback manner. As can be seen from the map in Figure 9.14, P-12's imagery was evolving throughout the process and much higher at the start (36% BRS versus 21% DEV). 12 minutes and 56 seconds for EVA was an outlier but with an average time per segment of 5.40 seconds, EVA is the quickest working stage of the process, and it is evident that P-12 was undertaking a high level of design work at this stage.

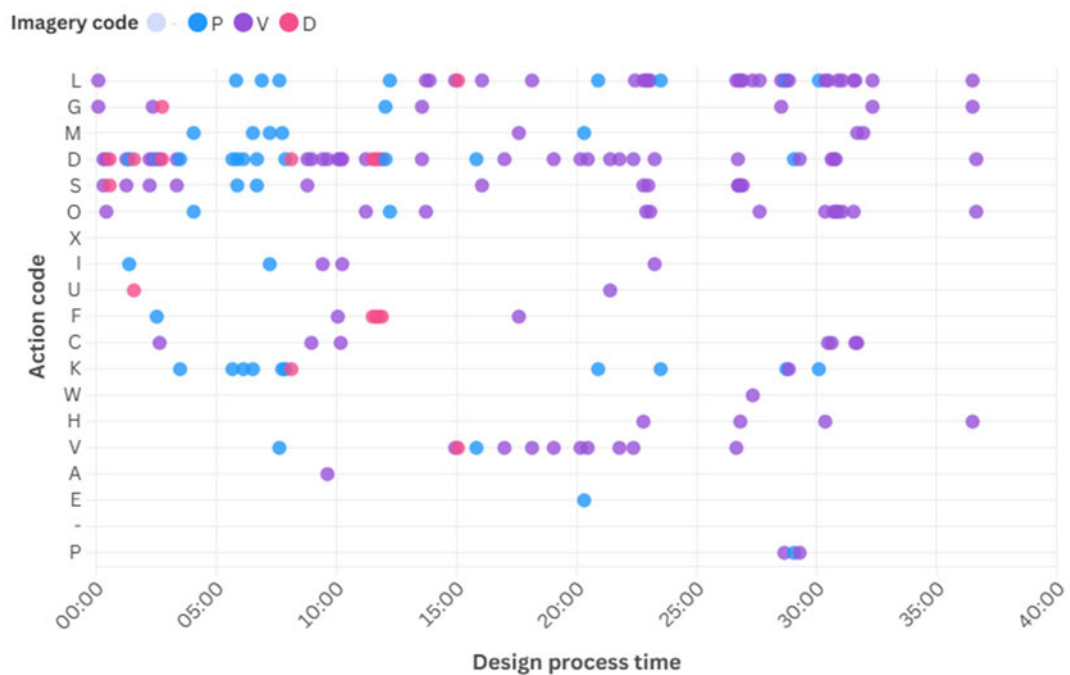


Figure 9.14: Imagery across the design process for P-12

From the imagery occurrence data, it can be seen that P-12's visuospatial coding was varied, with VR codes, over 30% VG codes, and an even distribution between VT and VP codes overall. Between stages, there is more VP and no VT in BRS, neither in GEN but an even distribution of each in EVA and DEV, indicating a clustered use of spatial and transformation imagery. VT is highest during the EVA stage which is likely due to the high number of decision and evaluative actions undertaken at this time. Additionally, no PP codes were recorded highlighting a lack of intention behind P-12's imagery experience.

While P-12's overall design process was laidback, they were active throughout with over 65% of all action codes being attributed to D-a, L-a, H-a and M-a. These action codes

also heavily occurred alongside imagery codes, as can be seen in the map in Figure 9.14. P-12 was only depicting approximately 30% of the time, but with longer segment times it is likely that each depiction was undertaken over a longer period. There were no N-a coded elements at all suggesting a constant focus within the design space throughout the design session, and only 6% X-a codes which indicate a talkative designer. Lastly, 6% of all action codes were V-a codes, which when compared to the maps in Figures 9.14 and 9.15, reveal clustered periods of decision making throughout the design process.

P-12 recorded a high number of links and link types throughout their design process, with 21 types of back links and 27 types of other links total. This reveals varied imagery behind what is being verbalised with up to 29 back links in one stage for GEN and 11 types for DEV. All stages for both back and other links are evenly distributed with no standout stage for exceptionally high or low levels of links. For imagery-action concurrent links, the total number of links and types is high overall at 188 over 68 types. With BRS containing a higher percentage of imagery use, but more links observed later in the design process, it confirms that P-12's process is evolving between start and end.

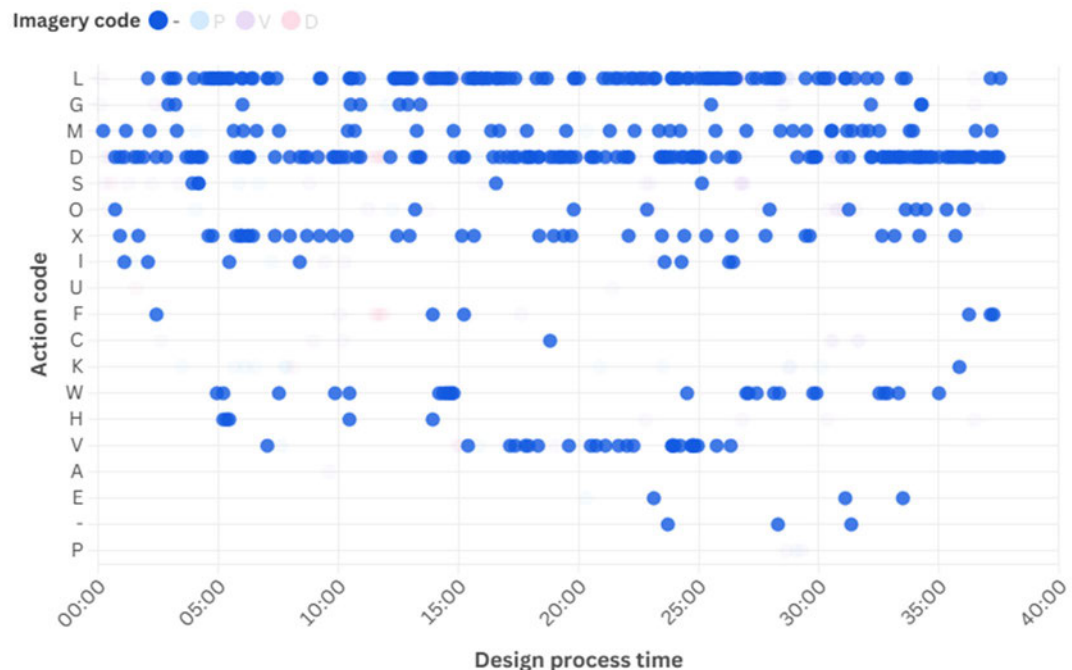


Figure 9.15: Action without imagery across the design process for P-12

9.2.10 The Focused Visualiser (P-13)

With an overall average segment length of 5.30 seconds, P-13 is another participant with a slow design process, although with a shorter design session time of under 30 minutes total. Their DEV stage was the slowest with an average segment length of 6.10 seconds, with GEN next slowest at 5.30 seconds, possibly connected to the higher levels of design actions in these stages. Clear in the two maps in Figure 9.16 and from the data in Chapter 8 is that there were almost eight times as many action codes logged as imagery codes, with only 20% of segments coded with imagery. BRS had the highest percentage of imagery of all stages at just over a quarter of segments coded. On the other hand, EVA had the lowest level of imagery at just 9% which equates to only seven occurrences for the entire stage.

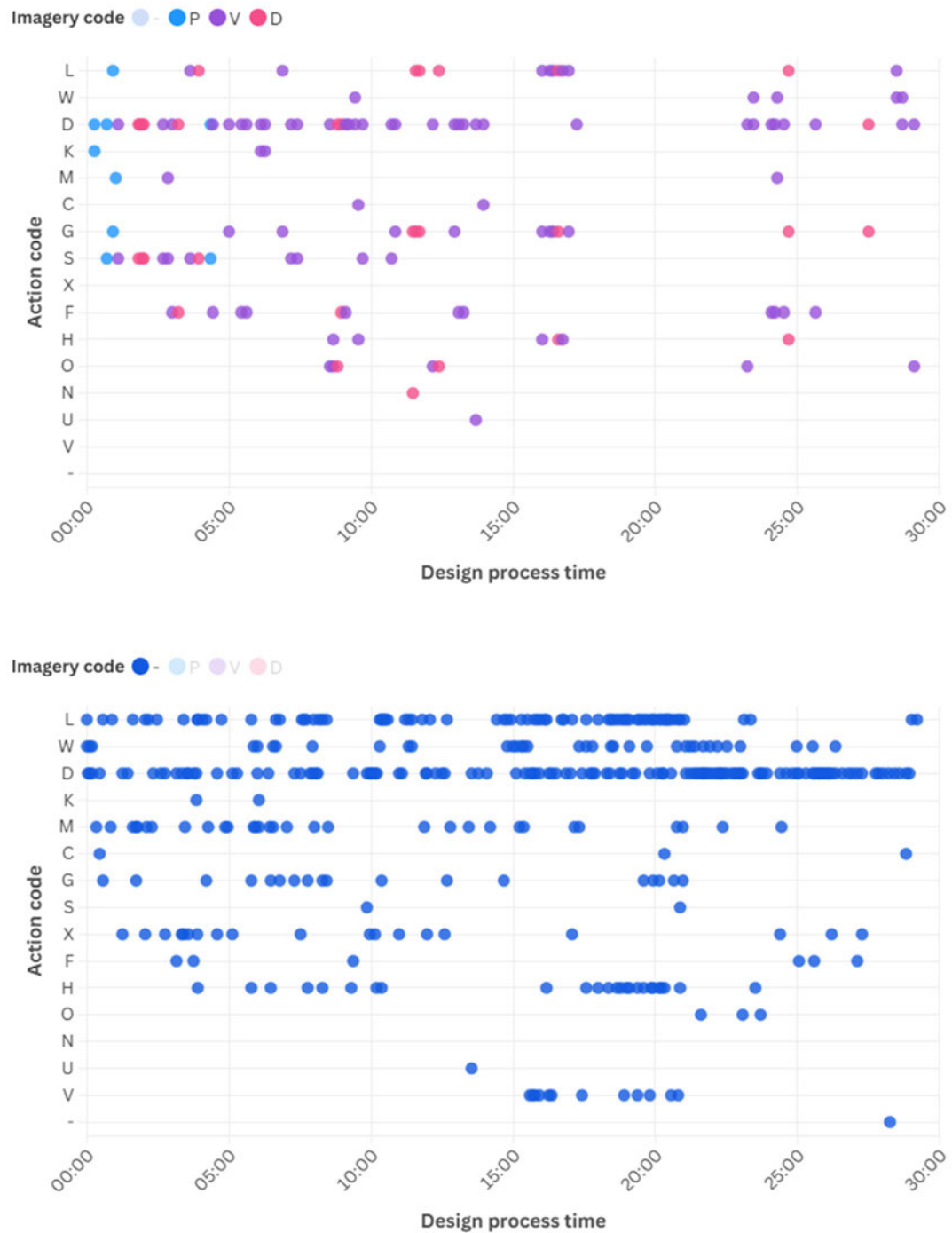


Figure 9.16: Imagery and action across the design process for P-13 respectively

P-13 logged a total of only five occurrences of PP imagery which indicates unintentional imagery experience, or a lack of awareness, and the map in Figure 9.16 reveals clustered imagery throughout the process. The imagery experience was lacking variation

across the visuospatial category with only three subcodes logged total, and majority as VG codes (three quarters of all Vx). The participant also indexed mostly new imagery codes at 72% total. Clear from the map in Figure 9.16 is that the imagery is changing and evolving throughout the design process, with only Vx imagery during BRS stage, somewhat unsurprising when generating new ideas for a design brief. Also evident in the maps is that GEN featured the highest level of imagery of all stages, but when considering the occurrence totals, there are only 26 occurrences of imagery in the stage, highlighting a lack of imagery experience overall for P-13.

P-13 logged a high level of cognitive-defined actions at 28%, despite there being four missing cognitive action codes of P-a, A-a, E-a and I-a. Further, P-13's D-a, L-a, H-a and M-a codes totalled 68% of all action codes suggesting an active design process, and there were only 4% logged as X-a indicating a talkative designer. P-13 has been designated as a "focused" designer based on the lack of N-a codes which signifies a focus within the design space, an over 10% focus on G-a, K-a and S-a codes revealing attention to the outcome of the design, and because the qualitative feedback from P-13's transcripts and actions indicated that there were less distractions to them and they displayed more commitment to finding a solution to the design brief.

P-13's design process imagery links featured a lot of missing codes and some very sparse link data at times. There were only 13 types of back linked codes and 18 types of other linked codes total, and while some elements such as DVv and PI featured links without coded elements elsewhere, there were a noticeably smaller number of links total. Additionally, there were only 118 imagery-action links over 46 types total, which is a low number of total links. However, it is noted that 46 is a significant number of link types highlighting variation in the type of imagery-action links, despite a low overall number. Of further note is that there were minimal PeA links with none in BRS or EVA and low numbers in DEV revealing a lack of consideration of perceptual actions alongside the participant's mental imagery.

9.3 Profiles of Imaging Designers

Following the analysis of each participant's individual design process and visualisation style, Profiles of Imaging Designers were generated by comparing overall data points and finding similarities between the ten participants. Analysis was undertaken on the

participant design process maps as well as on all quantitative data, and the matrix found in Figure 9.2 was developed as a result, with six clear traits of note: clustered, evolving and unintentional imagery, and active, quick and talkative actions. The imagery traits are those that depict the designer's imagery style throughout their design process, with actions explaining their design process itself. Each trait, as can be seen, has been attributed to at least half the total number of participants (P=5) to be included in the final profiles to ensure the trait has a high enough occurrence rate to be considered "regularly occurring". The final traits are detailed in this chapter, with each Profile of Imaging Designers comprised of two or more traits; at least one each from the imagery and action categories.

9.3.1 The Imagery Traits

The Clustered Imager

The clustered imager was defined based on map analysis of all participants, which can be found in Figures 9.3, 9.5, 9.7, 9.8, 9.9, 9.10, 9.11, 9.13, 9.14, and 9.16, with the maps clearly depicting P-1, P-4, P-5, P-7, P-9, P-12 and P-13 with varying levels of clustered imagery through their design process. P-1's mental imagery occurrences are clustered largely around the D-a actions, and the minimal Dx imagery codes they reported are clustered throughout the design process, rather than occurring individually. For P-4, their imagery was also clustered heavily around D-a, as well as L-a and O-a, with their minimal number of V-a (decision) codes clustered with imagery as well. With P-5, the Px imagery coding was largely clustered around the L-a and G-a action codes, with Vx heavily coded around depictions. P-7's overall imagery was largely not clustered, but with an exception during the EVA stage where all imagery was clustered together as one period. For P-9, their Px imagery was clustered at the start of the design process across various action codes, while Vx imagery was clustered towards the middle of the design session. P-12's imagery coding was heavily clustered around D-a action codes, across all categories of imagery, and there were particularly notable clusters of Dx imagery around the function (F-a) action category. Lastly, P-13's Vx imagery had notable clusters around L-a and G-a, with heavy clustering throughout the depiction actions, and a large number of Dx clusters at the start of the design process.

The Evolving Imager

The evolving imager details designers whose imagery style and experience changes over the different stages of the design process, whether by increasing, decreasing or acting in waves of experience differences. This has been calculated using the imagery occurrences over the course of each stage of the design process and supported by analysis of the process maps, which clearly depict changing mental imagery experiences. P-5's mental imagery experience evolves from a high of 38 in GEN to a low of 11 during DEV, while P-7's reaches a high of 32 at EVA before dropping to a low of five at DEV. For P-8, their mental imagery experience is stable throughout BRS, EVA and DEV at 13, 15 and 12 occurrences respectively, but jumps to a high of 24 during the GEN stage. P-9 reaches a low of 16 during EVA but then a high of 49 at DEV, while P-12 records a low of 16 during BRS and a high of 29 during GEN, and P-13 a high of 26 during GEN before dropping to a low of just seven during EVA.

The Unintentional Imager

While it could be argued that most of the participants are unintentional imagers due to an overall low level of PP codes, those assigned the unintentional imager trait are those with zero PP codes logged at all. These participants, P-3, P-7, P-8, P-12 and P-13, have no intentional referrals to their imagery experience and it can be assumed that, while they may be aware of their imagery following the design session, during the design session itself their consciousness is unintentionally verbalising any imagery experience. P-2 has also been included as an unintentional imager as while they were assigned one PP code, qualitatively their mental imagery appeared as scattered and unassuming, leading to the conclusion that their experience was also unintentional.

9.3.2 The Action Traits

The Active Designer

The active designer is defined here as a participant with a high combined percentage of D-a, L-a, H-a and M-a actions, with these four being the most active of all action codes. Also included in the PhA category are N-a and X-a codes but these are defined as inactive physical action codes. P-13 has the highest active code percentage at 68%, followed by P-9 with 65%, P-12 with 65%, P-2 with 64% and P-4 with 62%. While P-3 had a lower percentage overall, they have also been included as an active designer due to their average time of 3.48

seconds for every D-a, L-a, H-a or M-a coded segment, meaning that these segments were happening quickly and over shorter periods of time.

The Conversational Designer

The conversational, or talkative, designer is a participant with a particularly low level of silence throughout their design process, as calculated by their X-a action occurrence percentage. The most conversational designer, or the participant with the lowest X-a occurrence was P-9 with 3%, followed by P-13 with 4%, P-12 with 6% and P-1 with 8%. P-8 has also been included as a conversational designer despite having a slightly higher X-a occurrence of 14% due to their qualitative data revealing that the entire BRS stage of their design process was undertaken in their mind, via verbalisation alone, with no physical depictions undertaken.

The Hurried Designer

Finally, the hurried designer has been assigned to participants with the lowest average segment time throughout their design process, as calculated by their total design time divided by the number of segments total in their design session. The fastest designer by this metric is P-8 with an average segment time of 3.40 seconds, followed by P-3 with 3.50, P-9 with 3.90, P-4 with 4.00, P-2 with 4.10 and P-5 with 4.30. The average segment time overall when considering all participants was 4.30 seconds, meaning that P-7 was above the average time with 4.40 seconds per segment. However, due to P-7's short design time as discussed earlier in this chapter, they have also been considered as a hurried, or quick, designer.

9.3.3 Profiles of Imaging Designers

The Profiles of Imaging Designers are proposed as being composed of at least one of the three traits from each of the two categories: imagery and action. Theoretically, there are a total of 49 different variations of Profiles, as calculated by the sum

$$((n^x) - 1)^2$$

where n is the number of categories (two: imagery and action), and x is the number of traits per category (three), resulting in

$$((2^3) - 1)^2 = 49$$

or 49 combinations of traits total. Any of these 49 combinations would form one Profile of an Imaging Designer, and when considering the ten participants in this study, eight different combinations can be found in the matrix in Figure 9.2. Therefore, for these ten participants, there are eight different Profiles of Imaging Designers, which are categorised as follows:

1. The Conversational Designer with Clustered Imagery (P-1)
2. The Fast Active Designer with Unintentional Imagery (P-2 and P-3)
3. The Fast Active Designer with Clustered Imagery (P-4)
4. The Hurried Designer with Evolving-Clustered Imagery (P-5)
5. The Hurried Designer with Unintentional, Evolving-Clustered Imagery (P-7)
6. The Hurried-Conversational Designer with Unintentional, Evolving Imagery (P-8)
7. The Fast Active-Conversational Designer with Evolving-Clustered Imagery (P-9)
8. The Active-Conversational Designer with Unintentional, Evolving-Clustered Imagery (P-12 and P-13)

Regarding the varying Profiles found within the ten participants, as well as their own unique imagery maps and data, detailed in Chapter 8 and earlier in this chapter, it is clear that the mental imagery experience during the design process is a unique experience. Even amongst those sharing the same profile, the experience overall is diverse. For example, both P-2 and P-3 fall under the profile of The Fast Active Designer with Unintentional Imagery, yet their design process is defined by separate visualisation identifiers of The Restless Visualiser (P-2) and The Silent Visualiser (P-3). Similarly, both P-12 and P-13 were categorised as The Active-Conversational Designer with Unintentional, Evolving-Clustered Imagery, yet P-12's design process actions assigned them as The Leisurely Designer, while P-13's led to The Focused Designer, and so it is possible to conclude that while the Profiles detail the shared traits amongst some designers, it is still necessary to consider them individually in order to understand their unique experience of mental imagery in their design process.

9.4 Mental Imagery in Engineering Design

Overall, mental imagery was found to be inconsistent, with over seven times as many action codes than imagery codes when considering all participants, and over 99% of all imagery codes having concurrent action codes. The BRS stage was the slowest stage based on average segment length of 4.50 seconds, but had the highest occurrence of imagery at 29%,

while EVA was the fastest speed at 4.00 seconds average, and DEV contained the least amount of imagery at 19%.

It was observed when considering all participants' design processes that visuospatial imagery is most commonly the highest occurring form of visual mental imagery during the design process at 62% of all imagery occurrences. Visuospatial imagery refers to acts that can occur in visual mental imagery wherein an individual generates, transforms and rotates their visual imagery internally, to name a few examples. These elements of visual mental imagery are often the simplest to judge subjectively as they rely on physical, spatial elements of the physical world that designers are often familiar with. Counter to this, only 6% of all imagery occurrence was for the PI, or imagination, code and it is likely this lack of occurrence is due to the difficulty in subjectively judging imagination imagery. There is no definition of imagination that allows for exact measurement of the phenomenon within mental imagery, leading to difficulty in understanding when exactly a designer is undertaking imagination imagery, and when their mental imagery is, for example, made up of memories. The last finding from the imagery occurrences to note is that there were no DVv links, or no mention of vividness of visual mental imagery, despite there being many mentions of movement imagery. It is likely that this is due to the design brief selected since it assigns a high level of importance to the experience of movement in the solution generation.

The aim of this study has been achieved, with each participant being ascribed with their own visualiser identity that summarises their experience during the design process. Each participant has also been categorised into a Profile of Imaging Designer which accounts for any shared designer traits through imagery and action identifiers. Overall, this has allowed the mapping of ten diverse mental imagery experiences over ten different design processes and revealed that it is important to consider individualities of designers' mental imagery in design cognition research. It is highlighted that cognition research is subjective, and it would be necessary to study every individual designer to understand whether all traits and differences are accounted for, and it is possible that the counter traits noted in the matrix in Figure 9.2 may exist. While there was no evidence of them in the ten participants in this study, that does not mean it can be guaranteed that they do not exist in designers.

It is proposed that these findings begin the process of developing a shared definition and understanding of what is meant by mental imagery in engineering design. As has been demonstrated with this investigation, visual mental imagery in engineering design is

comprised of the varying elements of mental imagery a designer experiences while working through their own, unique design process. The elements include, but are not limited to, the vividness of a designer's mental imagery, their visuospatial abilities within their mental imagery, their intention to experience mental imagery, and their memories and imagination. As with anything in design cognition research, it is not feasible to rule out the possibility of other elements existing that have not been considered in prior research, and the shared definition proposed here is flexible to adaptation upon further research. By answering the knowledge gap proposed in Chapter 5, this work becomes an initial investigation into the diverse experience of mental imagery in engineering design and is a first step in developing a shared research language.

9.5 Summary

In summary of the study detailed throughout Chapters 8 and 9, confirmation of the existence of a varied experience of mental imagery in the design process was achieved, with a definition as a first step towards a shared understanding presented. Mental imagery in the engineering design process consists of elements at varying occurrences, with individual designer traits impacting and being impacted by the imagery experience of the designer. While this first step has been to understand the role of visual mental imagery in the design process, future work could be proposed which seeks to understand the role of multisensory imagery, how to measure imagination imagery, or the impact emotion has on the design process of students. There are many areas of mental imagery and cognition research that are not considered in this study, but what has been considered are the ways in which visual imagery differs within each designer, and allows for consideration of the experience in engineering design education by providing evidence of the intricacies of student designers' cognition, particularly when discussing the role of mental imagery.

Chapter 10: Implementation in education

10.1 Experience of Visual Imagery in Design Questionnaire (EVID)

10.1.1 Introduction

Psychometric measurement questionnaires are the state of the art in research for measuring the mental imagery vividness of individuals. With the limited availability of objective forms of measurements, questionnaires are a low-cost, subjective method of quantifying the vividness of mental imagery (Kozhevnikov *et al.* 2013). This chapter details the creation of a new psychometric questionnaire that measures the elements of the visual mental imagery experience within an engineering design setting, considering the holistic view of how an individual's experience is quantified. As discussed in previous chapters, there are many vividness questionnaires available for use, with several of them being employed as part of this research. However, none of those currently available are specific to the needs of engineering design research, and they largely focus solely on measurement the vividness of mental imagery. The findings in Chapters 8 and 9 have made clear the importance of considering mental imagery diversity in engineering design education. The coding in Chapter 8 gave useful data but took longer than is feasible for implementing into an education setting, and so a questionnaire inspired by the study would be a more suitable alternative.

The EVID questionnaire has been developed following research found in Chapter 3 (Mental imagery experiences), Chapter 7 (Mental imagery and design education), and Chapters 8 and 9 (Visual imagery in the design process). A recurring issue that was raised during the interviews in Chapter 3 was that the questionnaires used do not relate to design, with participants sensing a disconnect from what they have learned from the questionnaires about their own mental imagery experience, and the conversations about that experience in design. In addition to this, while the use of the PSIQ in Chapter 7 is relevant and justified as the most appropriate form of multisensory imagery measurement for the study, it would be beneficial to understand more about the elements of the participants' experience of mental imagery than only how vivid it is. It is interesting to see the correlation between mental imagery vividness and outcomes in the engineering design education modules but having a measurement of other elements of mental imagery, such as memory and imagination, would allow for greater insight into those correlations. This is supported by the coding scheme and

mental imagery experience maps developed in Chapters 8 and 9, which are evidence that the mental imagery experience during the engineering design process consists of various elements.

To ensure consideration of the different elements, a questionnaire that is malleable and adaptable to student responses, and is engineering design process specific, would be ideal. The interviews in Chapters 3, 8 and 9 are evidence of the richer data that can be collected when in-depth discussions on mental imagery take place, and when participants are allowed to fully detail what they are experiencing. For this to be successful, pre-existing research and questionnaires have been used as the basis and inspiration for the EVID, ensuring rigorous design of the questionnaire itself. This same methodology was used in Chapter 8's visual imagery in the design process study for the questionnaire portion. The questionnaire worked well for the study as an initial iteration of the EVID and made clear what is and is not useful when measuring mental imagery subjectively. For example, asking different variations of question about mental imagery intention did not add much to the overall understanding of mental imagery experience, while the questions of vividness and difficulty of different visuospatial elements allowed clear insight into how participants' mental imagery adapts during the design process. These findings should be taken into consideration when creating and establishing the EVID.

10.1.2 Methodology

Considering the FMIR detailed in Chapter 6, the EVID questionnaire is situated in the overlap of all three conceptual viewpoints, with a specific focus on visual mental imagery as a starting point for a potential future, multisensory questionnaire. The justification for this is that to create a multisensory version would be an additional complexity that is outside of the scope of this research, and it is necessary to start from the well-researched field of visual mental imagery, before adding in additional modality elements. The focus of the questionnaire is on what designers do in their mind (dimensions of imagery ability) and how they do it (imagery processes). Using the imagery coding scheme from Chapter 8 as the basis, the questions have been made up of imagery vividness, visuospatial imagery, and imagery process topics. The visual imagery in the design process study features the same mental imagery viewpoints and elements as is required for the questionnaire, and so utilising the coding scheme in this manner ensured the necessary inclusions are considered for the EVID.

As the focus of the research is to better implement mental imagery experience understanding into engineering design education, students were used as the participant. Students were provided with all necessary information prior to completing the questionnaire and were fully aware of the expectations and their right to withdraw consent. No information other than that necessary to data collection was gathered from the participants, while good data management practices were adhered to. The main output of this study is Version 1 of a questionnaire for measuring the experience of visual mental imagery in engineering design students.

As evidence has shown, the ability to map the mental imagery experience of engineering design students would be beneficial to design educators for improving their teaching and assessment of students. Using the imagery coding scheme found in Chapter 8 as a basis, the necessary considerations for questionnaire subtopics are vividness of imagery, visuospatial imagery (consisting of the generation, inspection, scanning, transformation, rotation, spatial ability, form, and fixation of imagery), and imagery processes (particularly the intentionality of imagery, and memory and imagination processes). The vividness of visual imagery can be integrated into other questions, for example by asking participants to transform their image then rate the vividness of the new image. Visuospatial imagery can be reduced to the generation, evaluation, transforming, rotating and spatial ability of imagery. Evaluation would consist of inspection and scanning elements, as all of these require an ability to assess the visual images they have within their minds. Further, the topic of the form the mental imagery takes can be included as an element of each subtopic, and fixation is irrelevant to this questionnaire as it is less of an element of mental imagery experience, and more related to wider design cognition. Finally, intention of imagery, memory imagery and imagination imagery subtopics are all included due to their relevance in the design process.

The format of the questionnaire was: participants were presented with a design brief before being asked questions based on the concept they have generated in their mind as a solution to the brief. It is important to note that the EVID could, theoretically, be adapted for design tasks related to a specific design field, i.e. for graphic designers or fashion designers. The EVID consists of five subsections: generation, evaluation, transformation, rotation, and spatial ability. A flowchart depicting the decision tree of the questionnaire can be found in Figure 10.1. To begin, each participant was asked to generate a solution within their mind's eye and then to rate the vividness of this image from zero to five, with zero representing

complete visual aphantasia, and five an image as vivid as real life (as per Marks 1973). If the participant selected “0”, they were asked if they have a concept, despite not visualising it. If they select “yes” they were asked follow-up questions on the form and elements of their concept before moving onto the next section, while if they select “no”, they were asked to explain how they would usually complete concept generation, before ending the EVID. If the participant selects any answer for vividness other than “0”, they were asked questions on imagery form, the elements of their concept, how difficult it was to generate, their intention to generate, their use of memory (with additional questions on vividness and difficulty), and their use of imagination imagery (also with additional vividness and difficulty questions). For the evaluation, transformation, rotation, and spatial ability subsections, the participants followed a slightly adapted format, as can be seen in Appendix 26. The difference for subsections two onwards is that if they select “0” on the initial vividness question, and then select “no” to the concept question, they continue to the next section. The questionnaire was created and distributed using Gorilla, a psychological testing platform allowing for adaptable questionnaires that can direct participants based on individual responses.

While, where possible, the VVIQ format of question and response has been used, or a close variation, the response format overall for the EVID varies between questions. As the EVID is measuring different elements of the mental imagery experience, it is not possible to use a one-size-fits-all method of responding i.e. the scale used to measure vividness is specific to vividness and would not work for questions of intent. While it is noted that this could cause some confusion, when a similar method was used in the questionnaire in Chapter 8’s study, it worked well alongside clear explanations. For vividness questions, a zero to five vividness scale is proposed, altering the VVIQ scale slightly. The reason for this is that during the Chapter 3 interviewees who reported aphantasia indicated some confusion with aphantasia being depicted as “1”, so “0” would be used to measure complete visual aphantasia. Ratings one to five would then be used to measure vividness with visual mental imagery, allowing for a clear low, high and midpoint score. The questions on any potential concept they have generated for those reporting aphantasia would be measured on a “yes” or “no” scale, while any questions on imagery form, elements of the concept, or what a participant’s usual practice for concept generation is in their own words. In addition to these, all difficulty questions would be answered on a one to five scale, and intent questions using “yes”, “no”, “unsure”, or “both”.

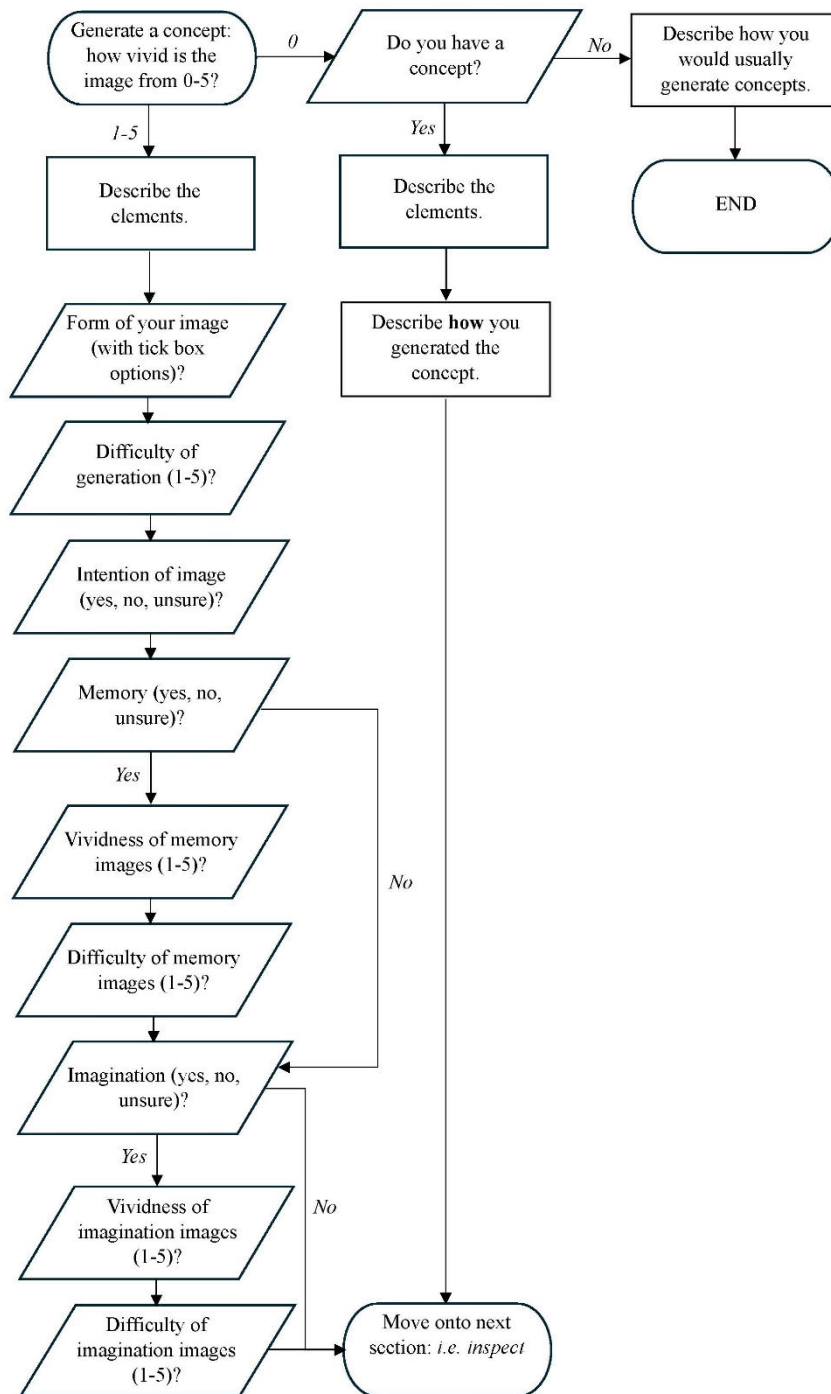


Figure 10.1: Flowchart of EVID decisions and moves

The final measurement was not intended for participants, and solely for research purposes, with no feedback provided to participants. The intent for the questionnaire is to develop a method of measuring engineering designers' visual mental imagery experience that is more streamlined than that detailed in Chapters 8 and 9. Participants have been analysed for average vividness over the five sections, average memory and imagination vividness, and overall form and intent. Additionally, the full responses have been considered with respect to the profiles detailed in Chapters 8 and 9 to discern if a similar analysis system can be developed for the EVID.

10.1.3 Results and analysis

Overall, the Gorilla software was intuitive to use for creation and distribution of the EVID and allowed for an easily adaptable questionnaire to be distributed for a wide range of participants. Due to an unfortunate error in the direction of responses, specifically if a participant responded to a vividness question with "5 – as vivid as real life", there was a misdirection for 17 of the total participants, leading to the data from these participants being unusable for full analysis. While full conclusions may not be available, the results of the study would allow for analysis of next steps in the research and potential future work. For the participants that did not respond with level five vividness at any point (22 total), the questionnaire succeeded in measuring their mental imagery experience during the design process. The final results allowed for initial conclusions to be drawn, and analysis of how the questionnaire could be adapted in the future.

39 participants completed the EVID, with all from fourth- or fifth-year engineering design courses at DMEM, and all gave explicit consent for the data provided to be used for research. As noted previously, 17 had to be excluded from the main portion of analysis due to an error in the questionnaire set up. Of the remaining 22, one responded with aphantasia at the generate portion of the EVID. While this demonstrated that the questionnaire was successful, as there was only one participant included in this sample and they did not provide enough detail to analyse fully, more research is needed on how aphantasia can be mapped and measured in engineering design before conclusions can be drawn.

The questions asking participants to detail the elements of their concept were positive as they made certain that the participant was generating a concept in enough depth to answer

the questions and not completing the questionnaire casually. Further, splitting the EVID into the visuospatial elements of generate, scan, transform, rotate and space, as taken from the coding scheme in Chapter 8, was an effective method for understanding different steps in the design process, by ensuring participants considered various elements of their mental imagery. There were some questions raised during completion to clarify terminology, so it is worth working to ensure all terminology is explained fully. The researcher received positive feedback about using the image of a concept being helpful for understanding their mental imagery during a design project, showing that the use of this, as opposed to general imagery questions, is justified.

Rather than relying on one vividness question, participants were asked to rate their vividness after different element tasks throughout the EVID, with five vividness responses for each participant. Additionally, vividness of concept, as opposed to general vividness questions, is more relevant when attempting to comprehend mental imagery experience in the engineering design process. The visuospatial elements chosen for inclusion are useful, in part due to their relevance in engineering design, but also to assist in examining mental imagery at different stages in the design process, as was seen with the results in Chapters 8 and 9. For example, one participant logged a 0.00 to 3.00 vividness range, while another a 1.00 to 4.00 range. There was an average vividness recorded of 1.80 to 4.00, with 76% of participants rating their vividness at a moderate level of between 2.80 and 3.80. At a future verification stage, it would be useful to validate the vividness questions against the PSIQ or VVIQ to decipher if the results of the EVID differ since they are more situational. With mental imagery in engineering design, as there are other considerations ongoing, such as the elements of the product, vividness may be impacted. During the study detailed in Chapter 8, it was discussed that one participant found concepts with more details challenging to visualise in full, so there is the potential of the same issue occurring with the EVID. When considering the responses participants gave to the element questions, there is a general consensus of a concept within a space or with many features, so there is potential of this impacting on imagery vividness responses due to complexity of the image.

Further comparisons have been made between participants who completed both the EVID and the PSIQ in Chapter 7. Nine participants completed both, and those with high or hyperphantasic responses in the EVID reported the same imagery level in the PSIQ. Contrary, the five who scored moderate in the EVID reported high level imagery vividness in the PSIQ.

While it is difficult to make an accurate comparison due to the different measurement scales used, it does show clear potential that mental imagery is being understood differently during the EVID, or during a design task, confirming the importance of exploring measurement during the design process.

Responses to the memory and imagination questions were analysed, with no clear conclusion on the results. The format in the EVID for questions of memory and imagination is unsuitable, with further research required on alternatives. Almost half of the 21 participants responded “unsure” to at least one element in memory, imagination or both at 9/21 (43%). Surprisingly, the result was higher for memory with all nine unsure in memory questions, and only four also unsure in imagination (19% of all participants). Potential reasons for this uncertainty are that participants are unclear how to comprehend the difference, or there are issues in judging imagination. As there are no clear correlations or conclusions to be made, it is recommended that more research into the elements of memory and imagination imagery in engineering design is undertaken.

Participants were asked about the form of their imagery over the five elements, with tick boxes given for 2D, 3D, sketching, photographic, memory and “other”. Most participants had consistent mental imagery form over all elements, with only 8/21 (38%) changing answers between elements. The most common response for form was 3D with 17/21 participants responding 3D for at least one element in their EVID at 81%. This was followed by photographic at 52% of participants (11/21), and memory at 43% (9/21). Memory was also the most changeable form with no participants responding that it occurred with every element. Only one person responded their imagery was in sketch form, and it was also changeable indicating a less common form for mental imagery. Lastly, there were no 2D or “other” responses logged for any participants.

Taking inspiration from the Profiles of Imaging Designers detailed in Chapter 9, identifiers have been found for the EVID participant responses based on measurable elements. These elements have been checked for similarities in vividness, difficulty and intentionality of imagery. The vividness identifiers have taken direct inspiration from Chapter 9 with “consistent” or “inconsistent” vividness based on responses to each element vividness question. The difficulty identifiers of “easy” and “difficult” were based on the overall responses and consistency to each element difficulty question. The “intentional” and “unintentional” identifiers are concluded on consistency of responses to the element intention

questions. Each participant could be a single trait or a combination of at most one from each trait set, with a total of 26 possibilities as per the below calculation:

$$\sum_{k=1}^3 \binom{3}{k} 2^k$$

where $n = 3$ and k = the number of traits, leading to the solution

$$\binom{3}{1} 2^1 + \binom{3}{2} 2^2 + \binom{3}{3} 2^3 = 6 + 12 + 8 = 26$$

or 26 total possible trait outcomes. In total, consistency was found in four participants and inconsistency in six, ease in seven and difficulty in one, and intentionality in nine and unintentionality in one. The overall results were as follows:

- Six participants with inconsistent imagery vividness
- One participant with difficult mental imagery experience
- Three participants with easy mental imagery experience
- Four participants with intentional mental imagery
- One participant with unintentional mental imagery
- Two participants with intentional mental imagery at a consistent vividness
- One participant with easy and intentional mental imagery at a consistent vividness
- One participant with easy mental imagery at a consistent vividness
- Two participants with easy and intentional mental imagery

Categorising the responses of participants in this manner allows more insight for both the researcher and the participant than vividness calculations alone. It is now possible to tell, for example, that while one participant has inconsistent moderate level imagery vividness with no other notable identifiers, another has easy and intentional mental imagery with consistently high-level vividness. While more work is required to verify these results and prove that other identifiers can or cannot be included, this shows promise of a more accurate method for measuring the diverse mental imagery experience in engineering design.

10.1.4 Summary

To summarise, the EVID has been evaluated as a useful first iteration of a new form of psychometric questionnaire to measure the mental imagery experience in engineering design. While further research is required on how to include memory and imagination measurement questions, and how to factor in aphantasia responses from participants, the overall findings were that the EVID was effective at measuring mental imagery experiences in engineering design. Asking participants to generate a concept for a design brief then answer questions on their generated internal outcome was successful as an alternative to the generic imagery questions found in existing questionnaires, such as the VVIQ. The inclusion of questions on varying visuospatial and intentionality elements was useful and allowed for interpretation of responses on more than just vividness of mental imagery. All results enabled the development of identifiers of the mental imagery experience and for detailed analysis of the individual mental imagery experience.

10.2 Sit on Your Hands design method

10.2.1 Introduction

Research seen in previous chapters, along with Edgecomb, Brisco and Wodehouse (2024), highlights that mental imagery can influence the engineering design process, particularly in student engineering designers. The current research found that the mental imagery experience in the engineering design process and amongst student engineering designers is diverse, yet there is a gap to incorporate this knowledge into educational settings. From this research, a design method has been developed with the view to bridging the gap. During the study detailed in Chapters 8 and 9, two key questions were noted while participants completed the think-aloud design task:

1. If they are describing their design out loud, is the researcher visualising what the designer is describing in the same way, and is there a shared understanding of how the design should look?
2. Would the think-aloud method be useful in an engineering design team setting?

These questions led to the development of a proposed new design method, titled Sit on Your Hands (SoYH). The SoYH method has been developed as a concept generation design method

for use in engineering design teams. The method encourages innovative thinking in engineering design teams, as well as inclusive consideration of cognitive diversity between team members.

As demonstrated throughout the thesis, there is clear evidence that engineering design students think, work and design in diverse ways, with a gap for incorporating this knowledge into educational settings. The proposed SoYH method would provide engineering design teams with a novel method for concept generation, wherein all physical elements of design are removed, and the design space is stripped back to the simplest tools of a designer's voice and mind. The method is intended to encourage concept generation through discussion alone, with team members instructed to "sit on your hands" to avoid temptation to use physical design, such as sketching, note-taking, and hand gestures – a common fallback element of design noted frequently in Chapter 9. By removing the ability for physical design, engineering design team members must consider carefully how to communicate the concept in their mind through words, putting focus on their mental imagery experience and that of their team members. Through this potentially paradigm shifting new concept generation method, it is anticipated that engineering design teams can become more empathic and inclusive of their fellow designers, with improved communication.

10.2.2 Methodology

The SoYH method has been evaluated and verified through approaches including a workshop at an international conference, and case studies in various engineering design classes. The workshop was undertaken as an evaluative first step by putting the method to design educators to gather their insights on if the method would be successful in their own classes. Following positive outcomes, the method was implemented into various engineering design classes in DMEM. While the workshop was planned to be delivered as a collaborative workspace for educators to share their experiences, the further case studies have been operated as real-life teaching experiences. In this, a lecture is delivered on the use of the SoYH method, with students asked to implement it into their teamworking on a design project. The outcomes to these case studies have been evaluated through the successful use of the method to generate concepts, and through the improved levels of empathy and communication between team members.

In April 2025 a proposal was drafted and submitted to the board of the 27th Conference on Engineering and Product Design Education (E&PDE) (Appendix 27) to hold a workshop at the 2025 event. This proposal was accepted in May 2025 and titled *Innovating Human-Centred Design Education: The Role of Mental Imagery in Inclusive Learning*. The workshop was chaired in collaboration with researchers from DMEM, and with the support of the Design Society's Design Education and Collaborative Design Special Interest Groups. The aim of the workshop was to understand if and how mental imagery can be integrated into education and explore the practicality and advantages of this knowledge through the SoYH method. The projected outcomes for the SoYH method are to encourage the consideration of diverse experiences in learning and teaching, and how cognitive diversity impact on student experience. It was anticipated that the engineering design teams employed for the case studies would gain an improved level of communication in their design projects and a greater sense of empathy towards their team members, as well as an understanding about their own way of working in engineering design.

10.2.3 Pilot Workshop at LeoCon 2025

Methodology

LeoCon is a local conference at the University of Strathclyde held for and by Postgraduate Research students in DMEM. The conference hosted the pilot of the SoYH method workshop, with all DMEM research students and staff invited to participate. The pilot workshop included a short lecture exploring mental imagery experiences to ensure everyone had a common understanding and language of the topic, an icebreaker where team members were each asked to complete a mental imagery measurement question and discuss with teammates, a team design task, and a discussion for sharing ideas. The team design task asked participants to complete a 25-minute design project as a team, using the SoYH method, followed by a ten-minute individual sketching task of the participants' internal image of the final solution. Participants were then invited to share their ideas and opinions on their experience in the workshop. The aim of the pilot was to gather insight on if the design task would operate as intended and give the results needed to evaluate the usefulness of the SoYH method.

Outcomes

On reflection, the lecture would have benefited from the inclusion of more definition of concepts. Limiting the lecture to the topic of understanding mental imagery ensured that participants were not overwhelmed. The icebreaker task of discussing their responses to the mental imagery question provided a common theme in discussion to allow participants to introduce themselves. The question was as follows:

Think of a 3D printer and consider carefully the image in your mind's eye. How vivid is this image from 1 to 5, with 1 being no image and 5 being as vivid as real life?

Three out of four participants rated their imagery at a four, while one rated their imagery at a one, which led to some interesting conversations about what exactly they are visualising. The format of this question mimics the wording and measurement of the VVIQ (Marks 1973) intended to ensure a solid foundation in research and to highlight the diversity in experience. The 3D printer topic was appropriate due to its engineering design theme, as all participants had the prior knowledge of 3D printing in this context.

The design brief was adapted from Campbell *et al.* (2024) and as follows:

Train stations and airports are often congested due to many people transporting large items in a confined space. Generate concepts for products that may reduce congestion in transportation hubs.

The team appeared cohesive in their effort to ideate solutions and converge towards an agreed solution. However, the breadth of directions the team could have explored was vast, and so it was decided that this brief will not be used in the final workshop in an attempt to have the teams generate a product concept. The design time should be increased to allow for the team to develop a shared understanding of their interpretation of the brief and the design constraints. The five-minute warning towards the end of the design session appeared to be a distraction as the team were finalising their solution and an alternative method of keeping time was needed.

The team's final solution was a transportation system for hand luggage located at the start and end of their airport journey (from check-in to boarding). The pilot team worked well together and developed their solution quickly and efficiently. Despite this, there were some areas that were noted for the possibility of issues in other teams. Personality of team members could lead to issues and should be watched for: team members being introverted or extroverted,

for example, could lead to some members talking over quieter members. Prior knowledge is another potential issue, as was seen with one participant's lack of design knowledge meaning they appeared to have less confidence in their ideas and solutions, resulting in a smaller contribution from them. Finally, imagery vividness may play a role in lower contribution and should be considered during analysis. The same participant reported low to no mental imagery, and it is difficult to know whether this or their lack of design knowledge led to their lower contribution without further discussions.

The sketching element of the workshop activity allowed the team members to think about how they individually interpreted the solution. There was a vast difference in the vision of the concept as represented by the sketches, and the style of representation, that the participants found interesting to discuss. This could potentially be due to differences in educational background: no design background, manufacturing design, systems design, and engineering design. The clear distinctions in the way they have chosen to represent their concepts, as seen in Appendix 28, may be explained by these differences in training, or it could be due to the diversity in their mental imagery experience, but conclusions are hard to determine without further exploration. The brief leading to a more system-based solution could also be a factor in this as it led to the team developing a concept that was based more on an overall transport system than a specific product solution.

10.2.4 Evaluate: Workshop at E&PDE 2025

Methodology

The E&PDE conference, held in September 2025, brought together design educators from across the globe with a vested interest in changing and improving engineering and product design education. The theme for the 2025 conference was Fostering Human-Centred Products and Services Design. The workshop aimed to bring together educators from across the sector with an interest in both design cognition and engineering education. No stipulations were placed on who could register for the workshop, so long as they had an interest improving educational and were willing to share their own experiences. Mental imagery experience was not considered as a prerequisite, but participants were asked to answer an imagery measurement question during the workshop to assist with analysis of the outcomes.

Five participants took part in the workshop as a single team. Upon arrival, the participants were asked to complete a short questionnaire with some personal details, listed below with all identifiable information removed for anonymity. Included in this questionnaire was a single mental imagery vividness response question so that each participant's mental imagery experience was understood. The topic of a "Lego minifigure" was suggested as a simple, well-designed item that many individuals would recognise. In the style of the VVIQ, participants were asked to rate the vividness of their visual mental image of a Lego minifigure on a scale of one to five, with one being no image and five being as vivid as real life. The responses are as follows:

- P1A: A Masters student in Design; reported their mental imagery vividness as one (no image), suggesting potential aphantasia.
- P1B: A PhD researcher in engineering design; reported their mental imagery vividness as two.
- P1C: A lecturer with a background in product design and entrepreneurship; reported their mental imagery vividness as four.
- P1D: An associate professor with a background in product design engineering; reported their mental imagery vividness as five, indicating potential hyperphantasia.
- P2A: A professor in industrial and interaction design; reported their mental imagery vividness as four.

The outcome of the mental imagery vividness question shows a large variation in the reported mental imagery experiences of the participants, giving a strong basis for trialling this method to account for mental imagery diversity in engineering design teams. While there were some language barriers, as will be discussed further in this chapter, the participants were open and accepting of the workshop activities and participated well together as collaborators.

The agenda for the session can be found in Appendix 29 and was presented to participants before the start of the first lecture portion, to ensure they were aware of what was expected and being asked of them throughout the afternoon. While there were two parts to the workshop, only part A has been included as relevant for this thesis. Part A of the workshop featured a short lecture, a team design activity using the SoYH method, and finally a discussion. The lecture covered the topic of Understanding Mental Imagery Experiences and aimed to ensure all participants had a shared knowledge of research on mental imagery

experiences before beginning the team task. The aim of the design task was to understand if the SoYH method was feasible, how it could be implemented into engineering design education, and what any advantages or disadvantages are related to inclusion of diverse learners in educational settings (specifically those with varying mental imagery experiences in engineering design courses). The team was given 35 minutes to develop a final solution to a set design brief and received a five-minute warning before the time was up. The five-minute warning was intended to encourage participants to begin verbally finalising design details. Following the initial 35 minutes design time, the team members were each given sketching materials and ten minutes to sketch their own interpretation or visualisation of their team's final solution, with no input or sharing of ideas amongst teammates. The aim was to understand if all team members are visualising the same concept, or if there are issues with the method leading to miscommunication. Finally, all participants were invited to share their ideas and discuss their findings and opinions from the design activity.

Outcomes

The team of five participants from different areas of education research were keen to participate as fully as possible in the workshop. The design brief randomly selected for the team was adapted from Campbell *et al.* (2024) and as follows:

Flooding is increasingly common across Europe and causes damage to property; transportation; and infrastructure. Generate a concept for a product to reduce the negative impacts of floodwater.

The longer time given to the educators for the SoYH activity proved beneficial as they required approximately 20 minutes to introduce themselves and gain a shared understanding of the brief. The team seemed content in sharing their own examples of issues caused by flooding, with some immediately comfortable with sharing personal and potentially emotional details about issues they have faced. Despite their working well as a team, it was only after around 25 minutes that the team started to finalise a solution to the design brief. Interestingly at the five minutes remaining reminder, one participant directly asked what other participants were visualising in their head, noting that this was the topic for the workshop. The team decided their final solution within the final minutes and confirmed between each other that they had an agreement of what the final concept should be: a product system that collects rainwater in a building and utilises it for necessary functions via a digital monitoring system. From a

researcher perspective, the team were successful in answering the design brief and navigating the absence of physical design stipulation in the SoYH method.

One element of the interpersonal working that was noted by the researcher was that personality plays a key role in how the team members interact and communicate with each other. P1A and P1B both had less input and appeared to be more reserved, although there was a language barrier, as will be discussed later in this section. The other three participants all provided equal input but had different focuses: P1C seemed focused on innovation, P1D on everyone's experience with the method, and P2A on supporting team members within the design work. Notably, P1D also repeatedly corrected themselves to not use their hands and made clear that they usually gesticulate a lot when talking, which proved to be a difficult thing to overcome. Other key personality impacts to note are that P2A jumped to solutions much quicker than P1C or P1D who were focused more on developing a shared understanding, and that P1C discussed previous design challenges within two minutes of starting the task, which highlighted a risk of fixation that they managed to avoid. It does appear that personality traits such as openness, introversion, and enthusiasm do impact on how well individuals navigate the SoYH method, but further research would be needed to determine the specifics of this, which are outside of the realm of this research.

Another interesting note taken was regarding the development of a shared understanding between team members. Team shared mental models support a design team's ability to collaborate effectively and reach a desired outcome in their project (Edgecomb, Brisco and Wodehouse 2025). The creation of these models often includes elements such as developing a shared understanding of the brief, shared goals for the outcome, and good levels of communication (Edgecomb, Brisco and Wodehouse 2025). While the stakes for this design task were low due to the absence of negative consequences, it was clear that it was important to the team to have a shared understanding of the brief and shared goals for the task. The team spent around ten minutes introducing themselves and sharing their own knowledge in order to assist in building this shared mental model, before attempting concept generation. Impact of personality is also clear here, as at around the five minutes remaining mark, P1D who had taken on a leadership role early in the task asked the rest of the team members what they were all "seeing" in their minds. The participant had taken note of the purpose of the workshop and decided to ensure that the potential cognitive diversity between team members was considered before the design was finalised.

There were several issues identified during the SoYH workshop session, including with the design brief itself. While the researcher tried to mitigate the risk of the team creating another product service system, as opposed to a standalone product, the multidisciplinary expertise in the design team and the use of a descriptive problem led to a systemic solution. The brief itself did encourage members to communicate, with the open nature of a brief regarding floodwater damage solutions leading to team members approaching it from the direction of their area of expertise, incorporating a shared goal and understanding of the problem. Unfortunately, there was a clear language barrier and potential cultural barriers evident throughout the task. While cultural barriers are harder to define and could be misinterpreted as differences between participant education and career backgrounds, requiring further research out with the scope of this thesis, language barriers are a key consideration for verification of the SoYH method. A clear example of this was with P1A's low confidence in the use of the English language, resulting in their inability to communicate efficiently with the rest of the team throughout the task. Another example makes evident the difficulty of not being able to use physical gestures as P1B, who's main spoken language is not English, was attempting to explain the term "warm" which proved difficult without being able to use hand gestures to explain the physical sensation they were referring to. These issues will have less impact where students share the same language and so need less consideration by educators who wish to employ this method within collocated settings. The method needs further verification for use in multidisciplinary or dispersed design teams.

The sketches, found in Appendix 30, were of a similar standard across the team, likely as all participants at the conference had a similar motivation for workshop attendance. P1A had a more artistic aesthetic to their sketch, with potential reasons for this being that they reported no mental imagery when asked, or as they are earlier in their career and have different priorities for a sketch. Further, P1B and P2A both sketched images that were more systematic in nature, with both participants coming from more technical backgrounds of engineering and industrial design respectively. Notably, their imagery vividness levels were very different with P1B reporting imagery vividness at a two, and P2A a four. It does appear that higher levels of imagery vividness (as seen in P1C, P1D and P2A) leads to slightly more detail in the sketch outcome, but it cannot be guaranteed this is a correlation without further investigation. It is just as likely that career stage has an impact on the sketch detail levels as the three participants with higher imagery vividness reported are also further in their academic careers, with all three being at lecturer or professor stage. While there would be no way to know for certain the

impact of mental imagery without further research, it is also not explicitly relevant to the verification of the SoYH method. Despite the method itself being derived from mental imagery research, the experience of mental imagery is not a stipulation for using or benefiting from the SoYH method, meaning it is not a necessary element to research and outside the scope of this thesis.

Overall, the feedback from participants was that the SoYH method would be a useful tool in various ways. One participant suggested that they would implement the method with new classes as a design-based icebreaker task, wherein students could use the intense forced-discussion element as a way to get to know each other's ways of thinking and designing. A further participant said they would implement it as a concept generation method to support inclusive learning and as another method for design teams to add into a portfolio of methods. Lastly, one participant suggested that while they would need further training on the method to implement, it was useful to begin considering the diverse needs of their students and the ways in which they teach.

Future work

Throughout the workshop, several issues of future research were identified. While not all of these can be considered within the scope of this thesis, the areas that are important for verification of the SoYH method will be prioritised. The issues raised are as follows:

1. What is the impact of multidisciplinary teams on the use of the SoYH method?
This question was raised after the pilot workshop and further queried during the E&PDE workshop, with both teams being multidisciplinary. While the team at the E&PDE workshop had similar backgrounds, there were still variations in their career and education experiences that may have impacted on their use of the SoYH method.
2. What would the impact of co-location or distribution of design team members be on the experience of SoYH? For the present research, the focus will be on co-located design teams to simplify the verification process for the SoYH method in the first instance, but it would be an interesting consideration for future work to understand if the SoYH method could work for distributed design teams and how.
3. Will the experience of the SoYH method be different for student teams? There are two parts to this question: would the experience be different if student

engineering design teams were given this method once they had already established a shared understanding of and goals for the brief; and would student engineering design teams have a different experience if they were given this method to undertake out-with a design project? This question was investigated through the verification case studies and the implementation of different formats for the SoYH delivery.

4. Would the participants' willingness to share their own experiences change if they (1) had access to other design methods, or (2) for student engineering designers? The first part to this question will not be considered for verification and is merely an interesting observation given the workshop participants' willingness to communicate via shared experiences. It was noted that it could be that if they were able to sketch or find other ways to communicate ideas, such as through research, they may not have been as willing to share any personal experiences.
5. By "no physical design", does this include communication tools such as head nodding and shaking? This was posed by P1D early in the SoYH activity and has been considered following the initial workshop. Since tools such as head nodding and shaking are purely communicative rather than featuring a design element, such as the use of hand gestures which can be utilised to explain size, it had been decided that these are not excluded from use.
6. How would the sketch outcomes be different if the participants all had a shared education and career background, such as with student engineering design teams?

To simplify the verification of the SoYH method, it has been decided that for the present project, the teams will be co-located and undertaking engineering design courses at DMEM. While it would be beneficial in future research to further verify if the method can be used as a design method in dispersed and multidisciplinary design teams, a staged approach to the verification of the method is more robust to ensure all elements are considered.

10.2.5 Verify: Design 2 module case study

Methodology

Following the feedback received from the workshop, it was decided to verify the SoYH method within a number of design classes at the University of Strathclyde. The Design 2 module (DM200) at DMEM challenges second-year engineering design students with a two-semester long design project. The module was selected due to the large cohort of 105 students, or 21 design teams, and as it allowed a case study of the SoYH method with students earlier in their design education and while they begin to learn about each other's abilities and their own design process. SoYH was presented to students as the first method for concept generation, avoiding any potential impact of previous work on their idea generation. They were given a brief lecture on the use of the method before 15 minutes of concept generation as a team. They were advised to generate a single concept as a team. As the teams had four weeks of prior design research on the challenge, it was assumed that they had a shared understanding on the design brief and the problem area they were investigating. The sketching element of the method was retained in the class, with all team members asked to sketch their own interpretation of the team's final concept immediately after the 15-minute design session. This allowed for a physical form of communication and reduces reliance on memory for the team members.

Results

82 students participated in the study, with 45/82 on the PDI course (55%), 28/82 on PDE (34%) and 9/82 on SDE (11%). Of the vividness of their visual imagery question, 4/82 rated their imagery at a 1/5 (5%), 1/82 a 2/5 (1%), 14/82 a 3/5 (17%), 32/82 a 4/5 (39%), and 31/82 a 5/5 (38%) (Figure 10.2). The number of aphantasia-level ratings of 1/5 is slightly higher than believed to be average (1-3% as per Zeman 2021), but at only 5% is not outside the realms of possibility. However, Zeman (2021) also found that hyperphantasia level mental imagery impacts approximately 3-5% of the population, so 38% of students scoring their imagery at a 5/5 is exceptionally high. This leads to the question of whether the one to five Likert scale is an accurate form of measurement, or if the question itself led to misjudgement of imagery experience.

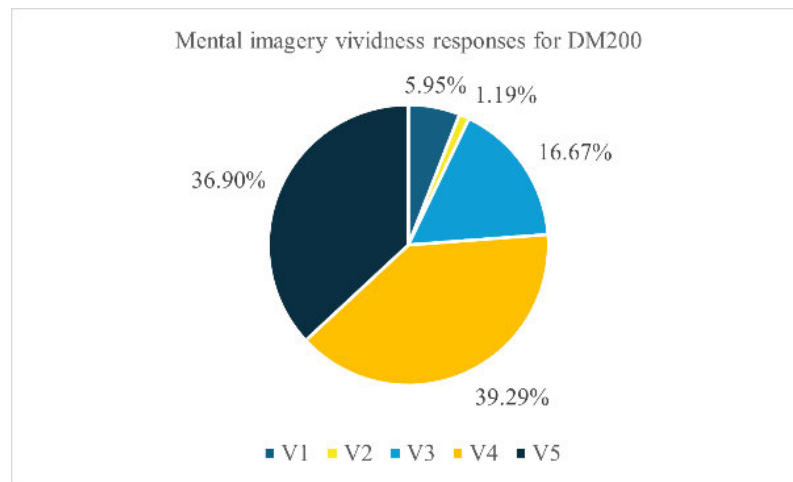


Figure 10.2: Pie chart of mental imagery vividness responses in DM200

Students were asked how useful they found the SoYH method and were asked to use an “extremely not useful” to “extremely useful” measurement scale. Only 5% of the class (4/82) said they found the method “extremely not useful”, 6% (5/82) found it “somewhat not useful”, 17% (14/82) found it “neither useful or not”, 59% (48/82) found it “somewhat useful”, and 13% (11/82) found it “extremely useful” (Figure 10.3). This shows an overwhelming level of support for the SoYH method from a second-year design module. When considering the usefulness responses alongside the vividness responses, there were mixed returns from each vividness rating for how useful the participants found it, with no findings of note that correlate between vividness and usefulness. All sketch outputs can be found in Appendix 31.

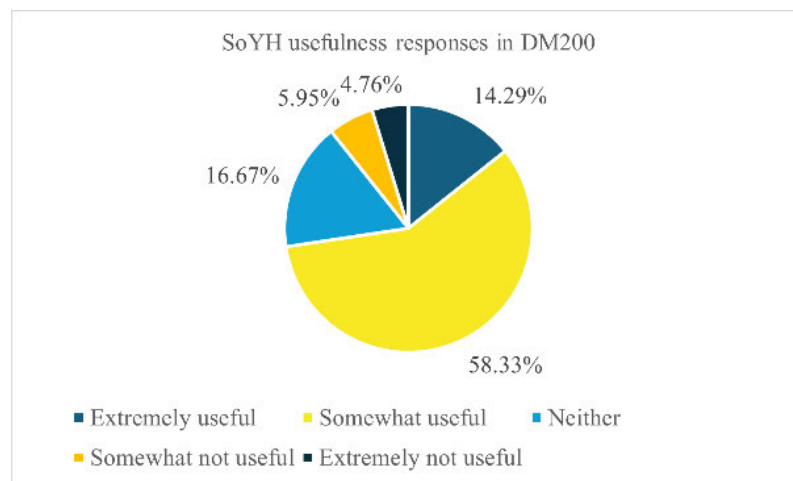


Figure 10.3: Pie chart of usefulness of SoYH responses in DM200

Of the 21 groups total in DM200, ten have been included for full analysis. The remaining 11 teams were excluded from full analysis due to missing sketch outputs or questionnaire responses. Team A included two PDI team members and two PDE members, with vividness responses of one, four, four and five, and usefulness responses of “neither” and three “useful”. The resulting sketches were very similar in style and aesthetics, with a clear shared understanding of the final concept. There were three PDI, one PDE and one SDE team members in Team H, with a single one-rated vividness response, one four-rated, and three five-rated. One team member rated the usefulness as “neither”, three as “useful” and one as “extremely useful”, and the team’s outcomes showed a clear shared concept but with different aesthetics. This resulted in very different sketch outputs with the SDE student’s sketch being a very literal interpretation, while the participant who rated their vividness at one included a large amount of detail and annotations in their sketch.

Team I was made up of two PDI, two PDE and one SDE members, with two four-ratings and three five-ratings on the vividness question, and a mixture of usefulness questions from “somewhat not useful” to “extremely useful”. The team’s sketch outputs were similar but with varying levels of annotation. Team I’s sketch differences appear highly dependent on sketching ability, with the team sharing similar aesthetic outputs. With three team members on PDI and two on PDE, Team K’s vividness was very similar throughout with three four-ratings and two five-ratings. Their usefulness responses were one “somewhat not useful”, one “neither” and three “somewhat useful”, and their sketch outputs showed very different aesthetics. While they had a clear shared understanding of their final concepts, sketch differences included varying styles and annotation levels, and some having a more system aesthetic to the sketch, with no clear correlation between vividness levels and sketch output. Team L had a similar mixed sketch output and were made up of three PDI, one PDE and one SDE students, with mixed vividness ratings of one, three, three, four and five. The team members rated the usefulness of the method either “somewhat useful” or “extremely useful”. One notable finding with the sketches between team members is that those with lower rated imagery vividness appear to rely more heavily on annotation.

Team N was made up of students from each of the three courses, with either four or five rated imagery vividness, and all rated the usefulness either “somewhat useful” or “extremely useful”. Their sketch outputs were all very different which leads to questioning if participant background has an impact. There was one PDI and two PDE members in Team O,

with two three-ratings and one five-rating for vividness, and two “somewhat useful” and one “neither” rating for usefulness. Counter to Team N, Team O’s sketches were all similar, with a whole system concept clear in their shared understanding. Team R’s sketch outcomes were also very similar, and the team was made up of two PDI, one PDE and one SDE student, with two three-ratings and two five-ratings for vividness. The team all rated the usefulness of the method as “somewhat useful”. All of Team T’s members also rated the method as “somewhat useful” and the team was made up of a mixture of students from the three courses, with vividness ratings of three and above. The team has a clear shared concept but with different aesthetic outputs. Finally, Team U was made up of two PDI and one PDE participant, with one three-rating and two five-ratings for vividness, and ratings of either “somewhat useful” or “extremely useful” for the method. Again, there were mixed aesthetics for Team U with a clear concept but no evident correlation on where the differences originated.

To conclude, while there was no evident correlation between vividness ratings and sketch outcomes, there was an overwhelming response from participants that they found the SoYH method useful for concept generation. The method is verified to work as part of a portfolio of design methods for concept generation within a pre-assigned design brief and pre-assigned teams, following a period of design research. It has been demonstrated that the method works for people of varying mental imagery experience and on different learning paths. Additionally, while the sketch outputs had no clear correlation with method or mental imagery, they were a useful addition to the method in order for design teams to not rely on memory of their developed concept, and so as to share creative aesthetics with their team members. Overall, the SoYH method worked well with the second-year design class and could be a useful addition to the teaching material in future.

10.2.6 Verify: Design Interaction module case study

Methodology

The Design Interaction module (DM411) at the University of Strathclyde is a fourth-year module for PDI students only, that aims to provide real-world insight into design work environments. The class was selected for a verification case study as the students were nearing the end of their undergraduate degree, and so, had a good understanding of their own design process and existing design methods. This allows for a critical view of the SoYH method in

comparison to previous methods they have been taught. As the class had no existing design project ongoing, the participants were given a new brief that encouraged them to be innovative:

There is a rising concern in society about the impact of screen time on children, and the need for fun and engaging non-screen toys as an alternative is ever present. Generate concepts for physical children's toys that avoid screens and limit technology use.

On the understanding that design methods are rarely followed in the same format each time they are used, it was decided that verification of the method in a different format would be beneficial. Rather than one period of 15 minutes design time, students were allocated 15 minutes for research prior to the design time, with the advice that they should avoid any form of sketching or physical design. Following this the teams generated three concepts in rounds of five minutes, with five minutes for sketching between each round. Teams were advised for each round to generate either an entirely new concept, or to build on their previous concept.

Results

There was a total of 15 participants in the Design Interaction class for the SoYH session, making up four teams: two teams of three, one of four and one of five. As with the previous case study, each participant was asked for feedback on the session and questions included rating the vividness of their visual mental imagery and how useful they found the method. For the vividness question, no participants rated their imagery at one, one rated their imagery at two, two at three, and six each at four and five (Figure 10.4). Over 80% of participants rated the usefulness of the method as either “somewhat useful” or “extremely useful” (Figure 10.5). It was noted while the study was ongoing that in future sessions, emphasis needs to be placed on the quick turnaround times as participants seemed to overestimate the length of five minutes. The teams all performed differently, with varying levels of engagement and sketch outputs, all found in Appendix 32.

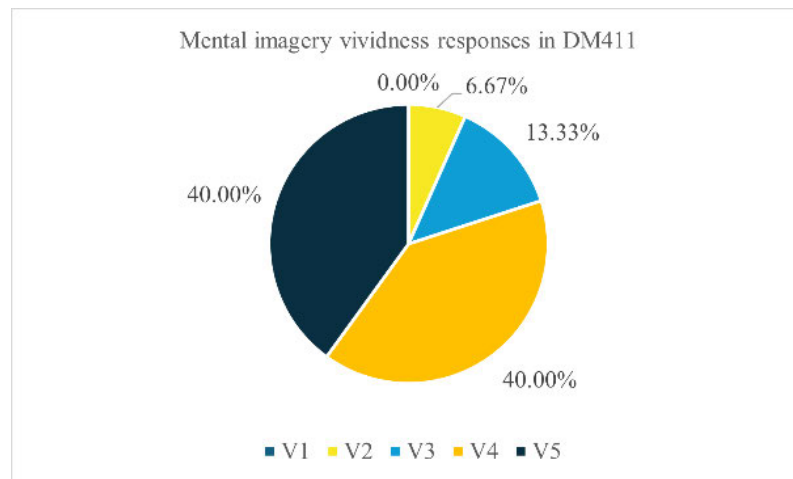


Figure 10.4: Pie chart of mental imagery vividness responses in DM411

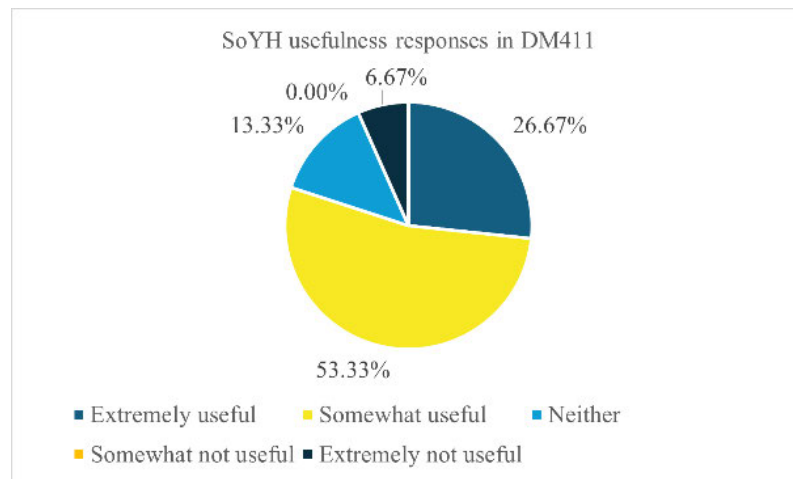


Figure 10.5: Pie chart of usefulness of SoYH responses in DM411

Team One rated their vividness five, four and three, and the usefulness of the design as “somewhat useful” or “extremely useful”. Overall, Team One appeared much less engaged in the session, particularly later on in the design rounds, which is clear from their sketch outputs. For sketch one there is a clear shared understanding, with all three sketch outputs similar in style and level of detail. By sketch two, while there was some clear building on the initial concept, communication levels have been lost with one participant’s sketch appearing to be a completely different concept. At sketch three all team members are designing different concepts with no shared understanding of their goals by this point.

Team two’s vividness ratings were five, five and four, with usefulness ratings of either “extremely useful” or “somewhat useful”; both team members who rated their vividness at

five also rated the usefulness at “extremely useful”. This team were very engaged and enthusiastic throughout the SoYH session, which is evident in the sketch outputs. For the first set of sketches, there is a clear shared concept but with different levels of details between team members. Sketch sets two and three have the same shared concept but with different focus elements, such as on the hinges or the overall aesthetic of the item.

Team three rated their vividness at five, three, five and four, with usefulness ratings of “neither”, “somewhat useful” or “extremely useful”. Interestingly, one participant gave ratings of three and “extremely useful” while another gave ratings of “five” and “neither” which appear to be mirrors of each other. Team three had a clear shared understanding throughout all sketch sets, with an obvious development on the previous concept in each round. For each round, each participant focused on a different element of the design, with some focusing in or expanding out each time. One participant of note sketched mostly elements or features of the design in sketch one and two but then focused on a whole product view for the final sketch.

Finally, team four rated their vividness at two, five and three four-ratings, with usefulness of one “extremely not useful”, one “neither” and three of “somewhat useful”. This team was engaged throughout the session, but the mixed feelings on the usefulness of the method is evident in their sketch outputs. For sketch one there were three different designed concepts in total, with a complete lack of shared understanding between participants. By sketch two the shared concept is beginning to develop, suggesting that the team were starting to become more comfortable with their task but, again, all sketches were very different in aesthetic and style. Finally, sketch three showed a clear shared concept but with different aesthetics, indicating a potentially underlying element of the team’s dynamics.

Overall, there were again no correlations found between individual mental imagery experience and the usefulness of the SoYH method. It can be assumed that, as with a lot of design methods, the method will be useful for the majority of students, but not all, depending on their preferences and personalities. The SoYH method has been verified here in a new format of shorter, faster concept generation rounds and when students are presented with a brand-new brief. It should be noted that with a new brief, it is necessary to allow students some research time at the beginning of the session, rather than having them delve straight into concept generation. As with the DM200 case study, the sketch sessions proved useful for creating a more detailed shared understanding between team members. In conclusion, the

DM411 case study verified a new format of the SoYH method and for inclusion in a fourth-year design class with students further in their academic careers.

10.2.7 Verify: Product Development module case study

Methodology

Product Development (DM306) is a third-year undergraduate engineering design module at the University of Strathclyde. The module teaches students methods and methodologies for design and development and features a semester long team project to design a product that solves a problem within an area identified by the team. Implementing SoYH into DM306 allowed for an exploration of the method at the start of concept generation within an established design team who have a reasonable understanding of the problem area. The format used for SoYH with the DM306 cohort was three rounds of concept generation through discussion alone with sketching between each round. The teams had five minutes to generate a concept as a team, followed by two minutes of sketching independently. They were advised to generate a new concept at each round and not to discuss sketches.

Results

There were 55 total participants in the SoYH session, with team numbers ranging from two to five per team on the day. Teams were questioned on vividness of their mental imagery experience and the usefulness of the method. None of the participants responded with an imagery vividness score of one, indicating none of the participants experience aphantasia. Only 13% of participants scored moderate or lower, and over 85% responded with a four or five-level imagery vividness, as seen in Figure 10.6. For the usefulness question, over 85% of participants said they found SoYH either “somewhat useful” or “extremely useful”, with only two responding “neither” and 11% that they found it not useful, with the results depicted in Figure 10.7. All sketch outputs can be seen in Appendix 33.

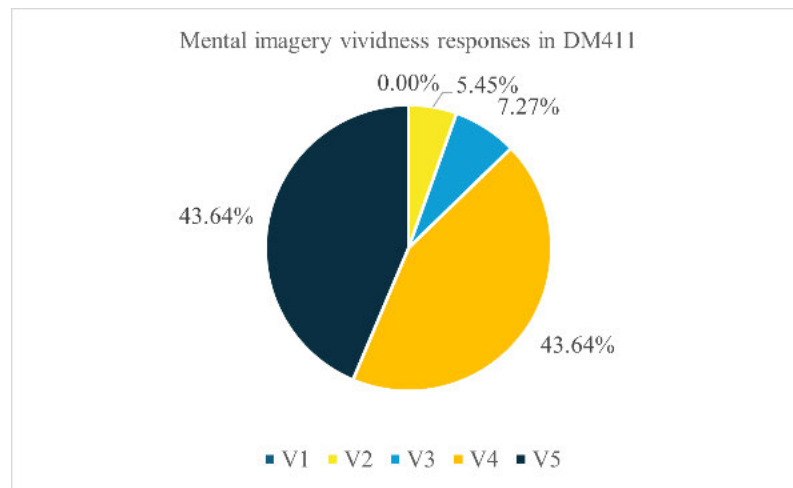


Figure 10.6: Pie chart of mental imagery vividness responses in DM306

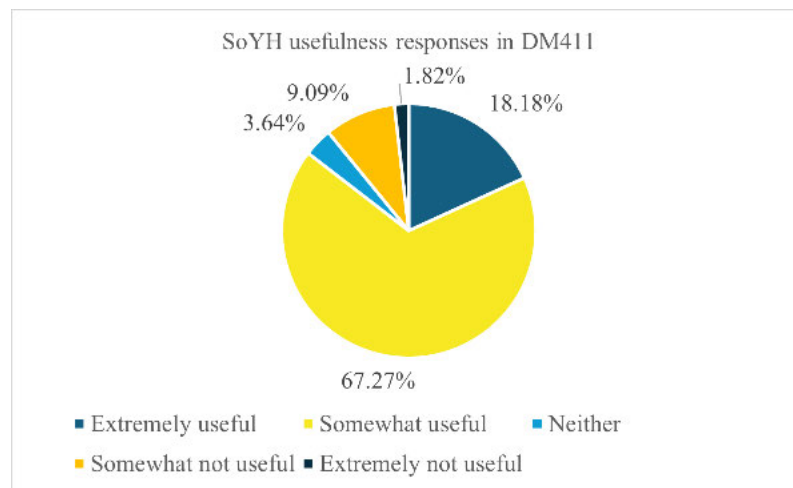


Figure 10.7: Pie chart of usefulness of SoYH responses in DM306

Of the 13 teams, six have been selected for further discussion due to the complete return of their sketch outputs with clearly identifiable concept generation rounds. Team three rated their vividness at mostly four, with one three, and usefulness was rated at one “neither”, three “somewhat useful” and one “extremely useful”. Their sketches throughout each round were different in terms of output, with round one showing similar sketches but clear difference in skill level, two a distinct output overall, and three a mostly similar output but with varying element details, such as shape. All of team four rated their vividness as a five, with three responding that SoYH was “somewhat useful” and one that they found it “somewhat not useful”. With concept generation round one, there was a clear difference in shared understanding of the output, with a large variation in sketch focus, style and aesthetic, yet with

rounds two and three the sketch outputs all had a distinct focus but were largely similar in concept. This leads to the question of if some teams require some time to develop a shared understanding, even on a pre-researched project.

The ratings for team six were more varied, with vividness responses of two, three, four and five, and usefulness responses of one “not useful”, three “somewhat useful” and one “extremely useful”. Overall, the sketches for all rounds were similar, but of note is that in rounds one and two one member each round differed from all other team members in sketch output, with round three depicting a clear shared concept. Team eight rated their vividness as either four or five, with usefulness as either “somewhat useful” or “extremely useful”. Again, team eight’s first round of concept generation produced very diverse sketch outputs, with rounds two and three clearly depicting the same concept with slightly varying details in the sketches. Team eight also recorded some interesting feedback in the questionnaire, with one participant stating that not using hand gestures made them communicate with more descriptive detail, which in turn allowed them to be more elaborate with their design suggestions, while another participant highlighted that the team enjoyed the conversation aspect and were excited to sketch after the five minute sessions.

Team nine rated their vividness at mostly four, with one member rating their vividness a five, and all except one member said the SoYH was “somewhat useful”, with the final member the only participant in DM306 who found the method “extremely not useful”. For the sketches, team nine also had a clear shared concept for rounds two and three but very distinct sketch outputs for round one. Finally, team ten all rated their vividness a four, and usefulness either “somewhat useful” or “extremely useful” and their sketch outputs were varied by round: round one sketches were similar throughout the team, while round two were very different across all members, and round three indicated a clear shared concept but with distinct sketch details from each member.

Overall, the majority of the DM306 case study participants found SoYH a useful method as part of their project, with the participants more invested in the session since it was included as part of a graded module project. The five-minute rounds again worked well with the participants, although it was noted that the first round still seemed to consist of them developing a shared way of working. A longer time was needed for the sketching portions, rather than the two minutes trialled, with it highlighted that a balance between enough sketch time without ending up too focused on sketch output is challenging to find. It would be an

intriguing point of future research to have participants use the SoYH method but with the responsibility of time keeping on the team themselves.

10.2.8 Summary

Following research on the mental imagery experience in engineering design, questions were raised on the impact of designing out loud on visualisation, particularly within engineering design teams. The questions led to the development of the SoYH method for team concept generation. SoYH aims to encourage innovation and inclusive thinking of cognitive diversity amongst team members by having engineering design teams generate concepts through discussion alone. The method removes all physical elements of design, from sketching to hand gestures and puts focus on the utilisation of mind and voice for communicating ideas. SoYH was evaluated at E&PDE 2025 through a workshop with a team of educators from various engineering and product design fields, with all educators confirming that they would use SoYH in future design classes. There were limitations to the method discovered with language barriers proving an issue, the impact of the team not working through a real-life project, and there being an impact to the team of brief selection and individual background. Future work has been suggested to consider how SoYH would work for multidisciplinary and distributed teams, and the impact of personality and individual background. The SoYH method has been verified through implementation into three engineering design modules with student engineering designers as a taught concept generation design method. The first case study was with a second-year class on an existing project, the second a fourth-year class with a new design brief, and the final case study was a third-year class with an existing project. The outcomes to the three case studies were positive, with more than 75% of participants overall stating they found SoYH useful. While no correlations have been uncovered between mental imagery experience and use of the SoYH method, further work to confirm this would be beneficial. Through the case studies, SoYH has been proven to work within a portfolio of design methods and at various levels of education within engineering design module classes. In conclusion, the SoYH method has been evaluated and verified as working within education settings for concept generation in engineering design teams and has been demonstrated to improve innovation, empathy and communication amongst team members.

Chapter 11: Conclusion

This research project aimed to understand the role that the experience of mental imagery has for engineering design, and how it is defined within the field specifically, with a view to use the knowledge to support inclusivity and diversity in engineering design education. This was to be achieved by answering three research questions:

- RQ1. How do engineering design students experience mental imagery during the design process, and can we map these diverse experiences?
- RQ2. By understanding the individual experiences, how can we define mental imagery in engineering design?
- RQ3. In what way can this understanding and definition be utilised to improve inclusivity in engineering design education for students?

Research question one was answered through a combination of the two key studies: mental imagery in design education (Chapter 7) and visual imagery in the design process (Chapters 8 and 9). The study in Chapter 7 presented evidence that there is diversity in the experiences of mental imagery in novice engineering designers and this diversity can have an impact on educational attainment. The study detailed in Chapters 8 and 9 confirmed *how* diversity occurs during the design process. This was accomplished through a protocol analysis study in which ten students worked through a recorded design task, with the recordings then segmented and coded according to a pre-determined coding scheme. The coded sessions were mapped onto a time-stamped design process and analysed alongside occurrence data, as can be seen in Chapters 8 and 9. The complete maps alongside the quantitative data presented a diverse experience of mental imagery in novice engineering designers and during their design process. These results further contributed to the success in answering research question two by enabling a definition to be developed towards a shared understanding of mental imagery in engineering design. The research throughout this thesis has provided evidence of the different elements in the mental imagery experience and culminates in Chapters 8 and 9 in which these elements are shown directly occurring in novice engineering designers. The definition is given as: visual mental imagery in engineering design is comprised of the varying elements of mental imagery a designer experiences while working through their own, unique design process. Finally, the research has been demonstrated to answer research question three, that it can be utilised to increase inclusivity in engineering design education by establishing that considering cognitive

diversity in education can have a positive impact on teaching, learning, designing and working. In this research, this has been executed through the development of the SoYH method for concept generation. The method has been developed in an effort to bridge the education gap with the knowledge that there is not a one-size-fits-all approach to engineering design education. The SoYH method provides engineering design teams with an alternative to the usual physical-focused design methods and encourages them to harness both their own experiences and their team members.

After an initial understanding was developed of mental imagery, a pragmatic research methodology was selected, along with a mixed methods approach. As discussed previously, the pragmatic research belief that there is an internal world within one's mind, and an equally important external world resonates with this project. Mental imagery is an entirely internal experience, while design focuses on interactions and experiences in the external world, so for mental imagery research in engineering design, both considerations are of equal importance. Due to the subjectiveness of mental imagery research, a complex mixed methods approach was deemed most appropriate so as to quantify the mental imagery experience while supporting findings with qualitative feedback from any, and all, participants. Novice engineering designers were selected following initial knowledge expansion work, where it was found that as novice designers are at the start of their career, they tend to have fewer external impacts on their design cognition. As research on mental imagery in engineering design is limited, this allowed for the research to start from the ground level in an engineering design career.

The research project was split into three stages: *knowledge expansion*, *research development*, and *investigations and reflections*. The *knowledge expansion* stage began with a state-of-the-art literature review that allowed for insight into mental imagery in different research fields. It was found that the experience of mental imagery differs between individuals, even amongst those in the creative fields, but given the subjectiveness of the phenomenon, it is difficult to define. A key output of the literature review was the knowledge gap of mental imagery in engineering design research, as it was found that research on the topic is extremely limited, and that there is a need for a shared definition and language for the experience of mental imagery in engineering design. Additionally, a criticism of the literature was detailed that there is often an oversimplification in the investigation of the experience of mental imagery (Dahl, Chattopadhyay and Gorn 1999; 2001; Goldschmidt 1991; Hart and Hay 2022).

Overall, the review led to an understanding of the current research and insights on next steps, with a decision made to continue building knowledge before making decisions on the final research approach.

Following the literature review, a set of five professional designers were interviewed and presented with a range of psychometric mental imagery questionnaires. This aimed to increase understanding of how to conduct mental imagery research. There were a number of issues raised from the completion of questionnaires including the impact a question has on the participant's cognition, that they were not relevant for design research, and that they only measure vividness, excluding a large portion of the mental imagery experience. While the questionnaires were overall deemed useful, it was clear that they need to be wider-ranging and more specific for design. The interviews allowed for better insight than questionnaires alone and encouraged conversations wherein the interviewee could freely discuss their experience without limitation. The interviews with the aphantasic designers enabled an appreciation to develop for the complexity of researching mental imagery diversity. While the insights from the conversations were instrumental in building an understanding of aphantasia in design, it did lead to questions about how the intricacies can be measured accurately and sensitively. Conclusions derived from the interviews allowed knowledge to be expanded through qualitative findings.

Running concurrently with the interview study was a small-scale study investigating the connection between design, emotion and mental imagery. The goal of this study was to investigate the impact of mental imagery and emotion on design module success. A negative correlation was uncovered but given the small participant pool of only ten students, it was determined these results were inconclusive. However, the study did lead to other insights, including that multisensory imagery in design is complex to study and considerations need to be made for how beneficial the outcomes would be to this research. The findings further supported the questionnaire issues that were uncovered during the interview study. One positive outcome was that the knowledge gained led to the researcher deciding novice engineering designers are a positive area of study for the research, which then allowed a research approach to be developed.

The next stage was *research development* and encompassed the development of a research focus and roadmap, and creation of a new framework for mental imagery research. The framework for researching mental imagery in design cognition (FMIR) was developed

and subsequently published as a paper for the 24th International Conference on Engineering Design in 2023 (Appendix 7). The framework was developed for mental imagery research and verified through its application to the field of engineering design (Macfie, Hay and Rodgers 2023). It consisted of three key conceptual viewpoints – imagery modalities, dimensions of imagery ability and imagery processes – and their interconnections. The FMIR was the first step towards developing a definition of mental imagery in engineering design and supported the contribution of the thesis to the research field through the encouragement of refocusing existing literature within the FMIR to reduce oversimplification of the experience of mental imagery within research. The purpose of the FMIR is to assist with mental imagery research across all academic disciplines, and with the knowledge that the FMIR could be expanded upon with future research. The framework was used to structure the remainder of the thesis, ensuring all studies and elements fell within its scope to justify their importance in answering the research aim.

The final stage of the research project was to define mental imagery experiences in engineering design education. This was to be accomplished through two key research studies: one considering mental imagery and design education, and one mapping visual mental imagery in the design process. The first study investigated and proved that higher reported mental imagery vividness leads to a lower performance in a design module, as had been indicated by the preliminary study in Chapter 4. The investigation asked novice engineering designers to complete the PSIQ and compared the responses with design module grades. Following statistical analysis on the PSIQ responses and module results, conclusively negative results were uncovered confirming that, of the cohorts investigated, novice engineering designers reporting higher mental imagery vividness levels see lower success levels in some engineering design modules. Future work on this topic would be beneficial to understand the reasons for this occurrence and if it can be generalised. Additionally, the study confirmed the need for a design-specific mental imagery questionnaire that asks participants about more mental imagery elements than vividness alone. The study contributed to the definition of mental imagery experience in engineering design.

The visual imagery in the design process study was undertaken with the aim to show that mental imagery experiences are diverse between engineering design students and throughout their individual design process. The study used the think-aloud method for design alongside protocol analysis to code design session transcripts and actions of participants.

These coded segments were then checked for coding and link occurrences to account for any quantitative analysis of the data provided. The small data pool of ten final participants is justified by the sheer volume of data acquired during the study, with each participant completing an hour and a half session, with two coded questionnaires, four coded design session stages, four interview sessions, ten imagery maps, and fifteen network maps, not considering the overall outputs that compared participants. The outputs of the study focused on the design sessions, with the interviews helping to confirm assumptions about the participant's mental imagery experience while they were working through their design process. The full study also included a questionnaire exploring the possibilities for creating a new, design-focused measurement of mental imagery in engineering design. The outcomes of this were successful and allowed insights into measuring elements of mental imagery during the design process in a simplified manner.

The visual imagery study cumulated in the development of Profiles of Imaging Designers. Each participant in the study was assigned a visualiser style according to their unique experience during their design session. Each participant's design process was mapped onto a timeline according to their mental imagery coding alongside their action outputs and investigated by overall process and stage (brainstorming, concept generation, concept evaluation, and concept development). Network maps for each participant were also created and considered but provided less significant feedback than other data outputs. Of the comparisons made between participants, three imagery and three action traits were uncovered as occurring regularly in participant sessions: clustered, evolving and unintentional imagery, and active, conversational and hurried design actions. It has been highlighted that a limitation of the small data pool means that their may well be additional common traits, but further research on more designers would need to be undertaken to confirm or refute this. The Profiles of Imaging Designers were made up of one or more imagery, and one or more action traits. There were 49 profile combinations in total, a number derived from a simple combinatorial summation. Eight of these profile combinations were seen in the ten participants which, when considered alongside the participant's visualiser identity, led to clear descriptors for their own mental imagery experience during the design process, for example The Fast Active Designer with Unintentional, Silent Imagery (P-3). Overall, in the study, mental imagery was found to be inconsistent with over seven times as many action codes than imagery codes. Further, it was concluded that the mental imagery experience changed over the design process depending on the participant, with some participants experiencing more imagery in the brainstorming

stage, or some experiencing longer imagery segments during concept evaluation, for example. Overall, the aim of the study was achieved, depicting a diverse experience of mental imagery across the design process, unique to the individual designer.

One of the intended outcomes of this research was to create a shared definition and language for mental imagery in engineering design. Part of this shared language is the decision to describe individual mental imagery as an “experience”. This was decided early on in the research as an attempt to create a simplified terminology for the individualities in mental imagery elements within one’s cognition. The phrase “mental imagery experience” allows for an easy manner in which to understand the phenomenon, whether the individual experiences very vivid and multisensory mental imagery, or whether they have visual aphasia. Further, a definition has been developed for how the phenomenon of visual mental imagery in engineering design is explained. During the studies detailed and from the FMIR, visual mental imagery in engineering design has been shown as being comprised of the varying elements of mental imagery a designer experiences while working through their own, unique design process. The elements include, but are not limited to, the vividness of a designer’s mental imagery, their visuospatial abilities within their mental imagery, their intention to experience mental imagery, and their memories and imagination. Further work may be required to expand this definition to include other elements and to define for multisensory mental imagery in engineering design.

Having decided on a research focus of novice engineering designers, with a view to creating more inclusive learning environments based on cognitive diversity, there was a gap found for incorporating the knowledge gained during this thesis into educational settings. In answer to this, two outputs have been developed from this research as methods for incorporating the knowledge within teaching and learning environments. The first of these is through the development of a new psychometric mental imagery questionnaire titled the Experience of Visual Imagery in Design Questionnaire (EVID). This is the initial iteration of a new questionnaire that attempts to map a participant’s mental imagery during the design process, as was seen in the visual imagery in the design process study, but in a streamlined format. While further work on the questionnaire is required to understand how to account for cognitive diversity, such as aphasia, or the impact of memory and imagination imagery, it was overall determined that the EVID functions for measuring mental imagery in engineering design students, particularly on visuospatial imagery topics. The inclusion of a design focus

using a concept brief worked well and allowed for identifiers of mental imagery experience to be developed as a measurement output. It was found that vividness of visual mental imagery could be measured by the average between each element as well as the consistency or inconsistency of a participant's responses, the ease at which they experience imagery could be determined by comparing the responses by element, and their intentionality could be understood by consistency of responding by element. Each participant could be a single identifier or a combination of three, leading to 26 total potential outcomes for determining mental imagery experience in engineering design. Examples of these outcomes include a designer with inconsistent, moderate level imagery vividness with no other notable identifiers, and another with easy and intentional mental imagery and consistently high-level vividness.

The second output for the research was the creation of a new design method, titled Sit on Your Hands (SoYH). SoYH was developed for concept generation and as a variation on the think-aloud method following questions raised during the Chapter 8 and 9 study sessions on what impact the method has on the individual listening, and if it could work in design teams. It is intended to encourage innovative thinking in engineering design teams and consideration of cognitive diversity between team members. The method works by removing all physical design elements, simplifying the design space to voice and mind alone. It has been found that the method was deemed useful by the majority of participants, but, as with most engineering design methods, does not work for every designer. This is acceptable given that it is meant to consider the diverse ways in which engineering designers think, work and design. The method was successfully evaluated at a workshop at the 27th International Conference on Engineering and Product Design Education and further verified by application in design classes. This was achieved in different ways, with one class undertaking the SoYH as a concept generation method in the middle of a full semester design project, having worked on the project for five weeks previously. Another class used the method with a new design brief via three fast-paced rounds of concept generation, while the final class working through three fast-paced rounds of concept generation on an existing project. Through these three case studies, SoYH is verified for use in a variety of situations and as part of a portfolio of design methods taught to engineering design students during their studies.

This project delivered research outputs in the form of the thesis itself, the FMIR, the EVID questionnaire, the SoYH design method, and the definition for mental imagery in engineering design. These outputs can be utilised for further research and for improving

inclusivity in engineering design education. The benefits of this research are that it has proven the experience of mental imagery is diverse between engineering designers and within their design process and provided insight on how the understanding can be utilised in engineering design education. At present, cognitive diversity in novice engineering designers is often not accounted for directly in education settings. The research in this thesis poses the question of why and if the consideration would improve design module success, leading to more well-rounded engineering designers. There are a range of uses for the research in this thesis, with the SoYH method adding to a portfolio of methods that engineering design students are taught throughout their studies, the EVID providing a simplified method to map and understand a student's individual experience, and the framework for researching mental imagery. Additionally, the research uncovered through investigations of the experience of mental imagery, supports the argument for revisiting previous literature to reduce oversimplification of the experience of mental imagery. Previous literature considering a one-dimensional view of mental imagery wherein the experience is simplified to solely one element, such as vividness of visual imagery (Hart and Hay 2022), or the simple existence of an image for translation or within a design setting (Dahl, Chattopadhyay and Gorn 2001; Tedjosaputro *et al.* 2017) can be re-examined in light of the findings throughout this thesis that the experience of mental imagery is complex and consists of various elements that interconnect in a manner unique to individual cognition. Further, the definition and shared language allow for simplified discussions on the topic. Finally, the research is useful for understanding that the cognitive diversity in individual engineering designers has an impact on their design process and that it should be considered to improve inclusivity.

There were a range of limitations that impacted the outcomes to this research, not least being those of time limitations. Firstly, the utilisation of novice engineering designers meant that studies needed to be carefully and precisely timed so as to account for the semester dates and their personal deadlines to minimise impact on their studies. Secondly, a supervisor change at the start of the second year of study, then again at the start of the third year of study had a minor impact on the research timeline due to the need to become accustomed to new researcher-supervisor dynamics. The main source of limitations for the research, however, was the impact of the topic itself. Mental imagery is a highly subjective experience that occurs entirely within one's own mind, and with a lack of objective measurement available making it a difficult topic to study, often akin to attempting to read a person's mind. As with any design cognition topic, to fully comprehend all experiences it would require every designer to be

studied to ensure that all individualities had been accounted for. Further, there was a lack of shared understanding or research on the topic at the start of the project, leading to a longer knowledge expansion time. Additionally, as the investigation of mental imagery throughout this thesis relies on language-based communication to translate and express mental imagery experiences of participants, this could introduce limitations of language skill differences, as well as a potential impact on the participants' capacity to express their experience. The participants in the various investigations throughout the thesis were assumed to be proficient in the English-language due to their enrolment on a course at the University of Strathclyde, where it is a mandate of acceptance. Furthermore, the questionnaires used throughout the investigations contained set questions and a specified grading system which enabled a simplified method of explaining mental imagery experiences, that removed the variable of communication method. A final limitation is that mental imagery is a wide-ranging topic that impacts many areas of cognition which often led to research becoming side-tracked by elements that the researcher needed to understand or investigate, such as aphantasia or the impact of sketching, an issue that the FMIR solved.

There are many areas of future work that the researcher would recommend as priorities for mental imagery research in engineering design. Firstly, that the experience of multisensory imagery in engineering design could be researched and defined throughout the design process. Given the nature of mental imagery, it can be assumed that multisensory imagery has a place in the engineering design environment, but the nature of how, and how it can be quantified requires additional research outside the timeline of this project. Secondly, while the researcher attempted to understand aphantasia within engineering designers at the start of the project, it was quickly decided that in order to understand the absence of mental imagery, the presence of mental imagery needed to be defined first. However, with the evidence provided of engineering designers working alongside aphantasia, it would be a point of interest to define this phenomenon. Further points of research include the direct impacts of mental imagery diversity on engineering design module attainment, and further work to fully develop the EVID questionnaire as a way of measuring the experiences. Lastly, more work on the impact of mental imagery experience on engineering design tool use is an important consideration for future research, particularly with the fast development of artificial intelligence (AI). Questions such as potential impact of AI images on mental imagery, or whether AI software could be utilised for mental imagery translation are only some examples of the potential wealth of research that could be undertaken in future projects.

To conclude, the research detailed in this thesis has succeeded in contributing to knowledge in a multitude of ways. It was confirmed through the research outputs that the mental imagery experience is diverse between individual engineering designers and across their own design process. Additionally, the thesis provides early-level research on mental imagery in engineering design, a topic that has not been widely researched prior to this project. It further shows the impact of mental imagery diversity on engineering design module success in students, and the impact it could have on inclusivity in engineering design education. A shared language was developed through the utilisation of the phrase “mental imagery experience”, and a new definition of mental imagery in engineering design. Finally, a framework for researching mental imagery was contributed to mental imagery research knowledge through its ability to be applied across research disciplines. This framework, alongside the findings throughout this thesis, invite a reconsideration of existing research, as detailed in Chapter 2, to remove previous oversimplification and view the mental imagery through its complex elements and their uniqueness within an individual’s cognition. In all, the project was successful in defining the diverse mental imagery experience in engineering design.

Reference List

Adharamandinka, M. & Junaidy, D. W. (2023) "Spatial mental imagery gap of student-studio lecturer and client-designer/architect by virtual reality and non-virtual reality" *Education and information technologies*, **28**(7): 8607-8643

Advance-he.ac.uk (2025) "Essential Frameworks for Enhancing Student Success." Retrieved 23/09/2025, 2025

Allen, A. D. (2010). "Complex Spatial Skills: The Link Between Visualization and Creativity." *Creativity Research Journal*, **22**(3): 241-249

Andrade, J., *et al.* (2014) "Assessing vividness of mental imagery: The Plymouth Sensory Imagery Questionnaire" *The British journal of psychology*, **105**(4): 547-563

Athavankar, U. A. (1997) "Mental imagery as a design tool." *Cybernetics and systems*, **28**(1): 25-42

Bainbridge, W. A., *et al.* (2021). "Quantifying aphantasia through drawing: Those without visual imagery show deficits in object but not spatial memory." *Cortex*, **135**: 159-172

Ball, L. J. & Christensen, B. T. (2019) "Advancing an Understanding of Design Cognition and Design Metacognition: Progress and Prospects." *Design students*, **65**: 35-59

Bensafi, M., *et al.* (2012) "Olfactory and Gustatory Mental Imagery: Modulation by Sensory Experience and comparison to Auditory Mental Imagery" *Multisensory Imagery*, **2012**: 77-91

Bilda, Z. & Gero, J. S. (2008) "Idea Development Can Occur Using Imagery Only." *Design Computing and Cognition*, **2008**: 303-320

Bilda, Z., Gero, J. S. & Purcell, T. (2006) "To sketch or not to sketch? That is the question." *Design studies*, **27**(5): 587-613

Brown, S. A., *et al.* (2020) "Externalizing Mental Images by Harnessing Size-Describing Gestures: Design Implications for a Visualization System." *Proceedings of the 2020 International Conference on Advanced Visual Interfaces*, **New York: ACM, 2020**: 1-9

- Callow, N. & Hardy, L. (2004) "The relationship between the use of kinesthetic imagery and different visual imagery perspectives" *Journal of sports sciences*, **22**: 167-177
- Campbell, G. *et al.* (2024) "Functional Activity and Connectivity during Ideation in Professional Design Engineers." *Design studies*, **2024**: 91-92
- Casakin, H. & Kreitler, S. (2011) "The cognitive profile of creativity in design." *Thinking Skills and Creativity*, **6**: 159-168
- Childers, T. L., Houston, M. J. and Heckler, S. E. (1985) "Measurement of Individual Differences in Visual versus Verbal Information Processing." *The Journal of consumer research*, **12.2**: 125-134
- Christensen, B. T. & Schunn, C. D. (2009) "The role and impact of mental simulation in design" *Applied cognitive psychology*, **23**(3): 327-344
- Chun, C. A. & Hupé, J.-M. (2016) "Are synesthetes exceptional beyond their synesthetic associations? A systematic comparison of creativity, personality, cognition, and mental imagery in synesthetes and controls." *British Journal of Psychology*, **107**: 397-418
- Cindioglu, H. C., Gursel, D. I. & Surur, E. (2022) "Proposing a novel mixed-reality framework for basic design and its hybrid evaluation using linkography and interviews" *International journal of technology and design education*, **32**(5): 2775-2800
- Creswell, J. W. and Creswell, J. D. "Qualitative, Quantitative, and Mixed Methods Approaches." Sixth edition; International student edition. Los Angeles: SAGE
- Croijmans, I. & Wang, Q. J. (2022) "Do you want a description with that wine? The role of wine mental imagery in consumer's desire to drink using the revised Vividness of Wine Imagery Questionnaire" *Journal of sensory studies*, **37**(1): e12712
- Croijmans, I., *et al.* (2019) "Measuring Multisensory Imagery of Wine: the Vividness of Wine Imagery Questionnaire" *Multisensory research*, **32**(3): 179-195
- Cui, X., *et al.* (2007) "Vividness of mental imagery: Individual variability can be measured objectively." *Vision Research*, **47**: 474-478
- D'Argembeau, A. & Van der Linden, M. (2006) "Individual differences in the phenomenology of mental time travel: The effect of vivid visual imagery and emotion regulation strategies" *Consciousness and cognition*, **15**(2): 342-350

- Dahl, D. W., Chattopadhyay, A. & Gorn, G. J. (1999) "The use of visual mental imagery in new product design." *Journal of marketing research*, **36**(1): 18-28
- Dahl, D. W., Chattopadhyay, A. & Gorn, G. J. (2001) "The importance of visualisation in concept design." *Design studies*, **22**(1): 5-26
- Designcouncil.org.uk (2025) "The Double Diamond." Retrieved 01/10/2025, 2025
- Dictionary.com (2026) "Imagination." Retrieved 03/02/2026, 2026
- Dijkstra, N., Bosch, S. E. & van Gerven, M. A. J. (2019) "Shared Neural Mechanisms of Visual Perception and Imagery" *Trends in cognitive sciences*, **23**(5): 423-434
- Dijkstra, N., *et al.* (2017) "Distinct Top-down and Bottom-up Brain Connectivity During Visual Perception and Imagery" *Scientific reports*, **7**(1): 5677-9
- Dijkstra, N., *et al.* (2019) "Between-subject variability in the influence of mental imagery on conscious perception" *Scientific reports* **9**(1): 15658-10
- Edgecomb, I. M., Brisco, R. and Wodehouse, A. (2024) "How designers think creatively: an exploratory study in the use of visual and emotional mental imagery." *Proceedings of the Design Society*, **2024**: 955-964
- Finke, R. A. & Slayton, K. (1988) "Explorations of creative visual synthesis in mental imagery." *Memory & cognition*, **16**: 252-257
- Floridou, G.A., Peerdeman, K.J. & Schaefer, R.S. (2002) "Individual differences in mental imagery in different modalities and levels of intentionality." *Memory & cognition*, **50**(1): 29-44
- Gaber, T. & Eltemamy, M. (2021) "Post-COVID-19 aphantasia" *Progress in Neurology and Psychiatry*, **25**(3)
- Gallace, A., Lacey, S. & Lawson, R. (2012) "Somesthetic Mental Imagery" *Multisensory Imagery*, **2012**: 29-50
- Gallagher, J. (2019) "Aphantasia: Ex-Pixar chief Ed Catmull says 'my mind's eye is blind'." *BBC News*, Retrieved 13/01/2022, 2022
- Gero, J. S. & Kannengiesser, U. (2004) "The situated function-behaviour-structure framework" *Design studies*, **25**(4): 373-391

- Gero, J. S. & McNeill, T. (1998) "An approach to the analysis of design protocols" *Design studies*, **19**(1): 21-61
- Gero, J. S. & Milovanovic, J. (2020) "A framework for studying design thinking through measuring designers' minds, bodies and brains." *DesignScience*, **6**
- Goldschmidt, G. (1991) "The dialectics of sketching." *Creativity Research Journal*, **4**(2): 123-143
- Goldschmidt, G. (1994) "On visual design thinking: the vis kids of architecture." *Design studies*, **15**(2): 158-174
- Goldschmidt, G. (2007) "To see eye to eye: the role of visual representations in building shared mental models in design teams." *CoDesign*, **3**(1): 43-50
- Goldschmidt, G. (2014) "Linkography: unfolding the design process" Cambridge, Massachusetts: The MIT Press 2014
- Hart, E. & Hay, L. (2022) "Do You See What I See? Exploring Vividness of Visual Mental Imagery in Product Design Ideation" *Proceedings of the Design Society*, **2022**(2): 881-890
- Hawley, J. (2022) "Windows to the soul: Pupils reveal 'aphantasia'." *ScienceDaily*, Retrieved 21/01/2023, 2023
- Hay, L., Cash, P. and McKilligan, S. (2020) "The future of design cognition analysis." *Design Science*, **6**
- Hay, L., *et al.* (2017) "A systematic review of protocol studies on conceptual design cognition: Design as search and exploration" *Design science*, **3**: e10
- Hay, L., *et al.* (2019) "The neural correlates of ideation in product design engineering practitioners." *Design Science*, **5**
- Herd, K. B. & Mehta, R. (2019) "Head versus Heart: The Effect of Objective versus Feelings-Based Mental Imagery on New Product Creativity." *The Journal of consumer research*, **46**(1): 36-52
- Hesse-Biber, S. N. (2010) "Mixed methods research: merging theory with practice." New York: Guilford Press

- Heuer, F., Fischman, D. & Reisberg, D. (1986) "Why does vivid imagery hurt colour memory?" *Canadian Journal of Psychology*, **40**: 161
- Heylighen, A. & Gero, J. S. (2011) "Studying the Unthinkable Designer: Designing in the Absence of Sight" *Design Computing and Cognition '10*: 23-34
- Holmes, E. A. & Mathews, A. (2010) "Mental imagery in emotion and emotional disorders." *Clinical psychology review*, **30**(3): 349-362
- Holtrop, D., *et al.* (2017) "Do Social Desirability Scales Measure Dishonesty? A Think-Aloud Study" *European journal of psychological assessment*, **37**(4): 274-282
- Isaac, A. R., Marks, D. F. & Russell, D. G. (1986) "An instrument for assessing imagery of movement. The vividness of movement imagery questionnaire" *Journal of Mental Imagery*, **10**: 23-30
- Ji, J. L., *et al.* (2022) "Emotional mental imagery generation during spontaneous future thinking: relationship with optimism and negative mood" *Psychological research*, **86**(2): 617-626
- Kan, J. W. T. & Gero, J.S. (2008) "Acquiring information from linkography in protocol studies of designing" *Design studies*, **29**(4): 315-337
- Kavakli, M. & Gero, J.S. (2001) "Sketching as mental imagery processing." *Design studies*, **22**(4): 347-364
- Keogh, R. & Pearson, J. (2018) "The blind mind: No sensory visual imagery in aphantasia" *Cortex*, **105**: 53-60
- Kokotovich, V. & Purcell, T. (2000) "Mental synthesis and creativity in design: an experimental examination." *Design studies*, **21**(5): 437-449
- Kosslyn, S. M. (1980) "Image and mind." Cambridge, Mass. London: Harvard University Press
- Kosslyn, S. M., Behrmann, M. & Jeannerod, M. (1995) "The cognitive neuroscience of mental imagery" *Neuropsychologia*, **33**(11): 1335-1344
- Kozhevnikov, M., *et al.* (2013) "Creativity, visualization abilities, and visual cognitive style." *British journal of educational psychology*, **83**(2): 196-209

- Kumar, R. (2018) "Research methodology: a step-by-step guide for beginners." Fifth edition. Los Angeles: SAGE
- Laeng, B. & Sulutvedt, U. (2014) "The Eye Pupil Adjusts to Imaginary Light" *Psychological science*, **25**(1): 188-197
- Lawrie, E., Hay, L. & Wodehouse, A. (2023) "A Classification of methods and Constructs in Design Cognition Research" *Design Computing and Cognition'22*, **2023**: 97-114
- Leblebici-Başar, D. & Altarriba, J. (2013) "The Role of Imagery and Emotion in the translation of Concepts into Product Form" *The Design journal*, **16**(3): 295-314
- LeBoutillier, N. & Marks, D. F. (2003) "Mental imagery and creativity: A meta-analytic review study." *The British journal of psychology*, **94**(1): 29-44
- Lee, J. H. and Ostwald, M. J. (2024) "The impacts of non-perceptual cognition (NPC) on design process and ideation." *Research in engineering design*, **35**(4): 355-372
- Macfie, R. L., Hay, L. A. and Rodgers, P. (2023) "A framework for understanding mental imagery in design cognition research." *Proceedings of the Design Society*, **2023**: 171-180
- Maciel, I. M., *et al.* (2021) "Mental Imagery for Multisensory Designers: Insights for Non-Visual Design Cognition." *Design for Tomorrow*, **1**(221): 109-118
- Marks, D. F. (1973) "Visual imagery differences in the recall of pictures" *British Journal of Psychology*, **64**: 17-24
- Martindale, C. (1990) *Creative Imagination and Neural Activity. The Psychophysiology of mental imagery: theory, research, and application.* Amityville, NY, Baywood Pub. Co.
- Merriam-Webster.com (2025) "Imagination." Retrieved 06/03/2025, 2025
- Milton, F., *et al.* (2021). "Behavioral and Neural Signatures of Visual Imagery Vividness Extremes: Aphantasia versus Hyperphantasia." *Cerebral Cortex Communications*, **2**(2)
- Nanay, B. "Multimodal mental imagery" *Cortex*, **105**: 125-134

- Network, A. (2021) "Aphantasia Network." Retrieved 21/01/2022, 2022
- Palmiero, M. and Piccardi, L. (2020) "Is Visual Creativity Embodied? Thinking Aloud While Performing the Creative Mental Synthesis Task." *Brain science*, **10**(7): 455-12
- Palmiero, M., *et al.* (2009) "Mental imagery generation in different modalities activates sensory-motor areas" *Cognitive processing*, **10**(2): 268-271
- Palmiero, M., *et al.* (2015) "Domain-Specificity of Creativity: A Study on the Relationship Between Visual Creativity and Visual Mental Imagery." *Frontiers in psychology*, **6**
- Palmiero, M., *et al.* (2016) "The Relationship between Visual Creativity and Visual Mental Imagery in Ageing." *Psychology of Creativity*. G. B. Moneta and J. Rogaten, Nova Science Publishers, Inc.
- Pearson, D. G. (2007) "Mental Imagery and Creative Thought." *Imaginative Minds*. I. Roth, British Academy Scholarship
- Pearson, J. (2019) "The human imagination: the cognitive neuroscience of visual mental imagery." *Nature reviews – Neuroscience*, **20**(10): 624-634
- Pearson, J., Rademaker, R. L. & Tong, F. (2011) "Evaluating the Mind's Eye: The Metacognition of Visual Imagery" *Psychological science*, **22**(12): 1535-1542
- Psytoolkit.com (2022) "Mental Rotation Test." Retrieved 05/10/2022, 2022
- Pugh, S. (1990) "Total design: integrated methods for successful product engineering", Wokingham, England: Addison-Wesley
- Rademaker, R. L. & Pearson, J. (2012) "Training visual imagery: Improvements of metacognition, but not imagery strength" *Frontiers in psychology*, **3**: 224
- Rhodes, J. W. (1981) "Relationships Between Vividness of Mental Imagery and Creative Thinking." *The Journal of creative behavior*, **15**(2): 90-98
- Richardson, J. T. E. (1991) "Imagery and the brain." *Imagery and cognition*. New York, Springer-Verlag: 1-46

- Roberts, R., *et al.* (2008) "Movement imagery ability: Development and assessment of a revised version of the vividness of movement imagery questionnaire" *Journal of sport & exercise psychology*, **30**(2): 200-221
- Shealy, T., *et al.* (2023) "Changes in cognition and neurocognition when thinking aloud during design" *Proceedings of the Design Society*, **3**: 867-876
- Sheehan, P. W. (1967) "A shortened form of Betts' Questionnaire Upon Mental Imagery" *Journal of Clinical psychology*, **23**: 386-389
- Subirats, L., *et al.* (2018) "Age and gender differences in motor imagery" *Journal of neurological sciences*, **391**: 114-117
- Suwa, M., Purcell, T. & Gero, J. (1998) "Macroscopic analysis of design processes based on a scheme for coding designers' cognition actions" *Design studies*, **19**(4): 455-483
- Taruffi, L. & Küsser, M. B. (2019) "A Review of Music-Evoked Visual Mental Imagery: Conceptual Issues, Relation to Emotion, and Functional Outcome" *Psychomusicology*, **29**(2-3): 62-74
- Tedjosaputro, M. A. & Shih, Y. C. A. (2019) "Perceiving Design Processes as Embodied Experience" *Research into Design for a Connected World*, **135**: 21-31
- Tedjosaputro, M. A., *et al.* (2014) "Multidisciplinary Design Behaviour Using Sketching and Mental Imagery: A Literature Review and Considerations for Future Research." *ICoRD'15 - Research into Design Across Boundaries*, **1**: 27-37
- Tedjosaputro, M. A., *et al.* (2017) "Differences in Sketches and Mental Imagery in Ideation Stage of Novice Designers" *Research into Design for Communities*, **1**: 49-60
- Tedjosaputro, M. A., *et al.* (2018) "Interplay of Sketches and Mental Imagery in the Design Ideation Stage of Novice Designers." *The Design Journal*, **21**(1): 59-83
- Tedjosaputro, M. A., Shih, Y.-T. and Gero, J. S. (2019) "A Visualization Tool to Investigate the Interplay of External and Internal Processes." *Design Computing and Cognition '18*, **2018**: 699-686
- Van der Schaaf, M., Bakker, A. & Cate, O. (2019) "When I say... embodied cognition" *medical education*, **53**(3): 219-220

Voyer, D., *et al.* (2020) "Sex Differences in Tests of Mental Rotation: Direct Manipulation of Strategies with Eye-Tracking" *Journal of experimental psychology*, **46**(9): 871-889

Zeman, A. (2021) "Blind Mind's Eye: People with aphantasia cannot visualize imagery, a trait that highlights the complexities of imagination and mental representation." *American scientist*, **109**(2): 110

Bibliography

Allbutt, J. *et al.* (2011) “Vividness of visual imagery and social desirable responding: correlations of the vividness of visual imagery questionnaire with the balanced inventory of desirable responding and the Marlowe-Crowne scale.” *Behaviour Research Methods*, **43**(3): 791-799

Barnett, K. J. & Newell, F. N. (2008) “Synaesthesia is associated with enhanced, self-rated visual imagery.” *Consciousness and cognition*, **17**(3): 1032-1039

Bartlett, K. A., Camba, J. D. & Gero, J. S. (2023) “Is the PSVT:R Suitable for Evaluating Spatial Skill in Design? A Critique.” *Design Computing and Cognition 2022*, **2022**: 115-126

Benedek, M., *et al.* (2014) “To create or to recall? Neural mechanisms underlying the generation of creative new ideas.” *NeuroImage*, **88**(100): 125-133

Bigelsen, J. & Schupak, C. (2011) “Compulsive fantasy: Proposed evidence of an under-reported syndrome through a systematic study of 90 self-identified non-normative fantasizers.” *Consciousness and cognition*, **20**(4): 1634-1648

Campos, A. (2014) “Gender differences in imagery.” *Personality and individual differences*, **59**: 107-111

Campos, A. & González, M. A. (1993) “Vividness of Imagery and Creativity.” *Perceptual and motor skills*, **77**(3): 923-928

Cole, C., *et al.* (2020) “How Engineering Design Students’ Psychological Safety Impacts Team Concept Generation and Screening Practices.” *ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, **2020**

D’Angiulli, A. (2020) “Vividness, Consciousness and Mental Imagery: A Start on Connecting the Dots.” *Brain sciences*, **10**(8):500

Dawes, A. J., *et al.* (2020) “A cognitive profile of multi-sensory imagery, memory and dreaming in aphantasia.” *Scientific reports*, **10**(1): 10022

- Dougherty, P., *et al.* (2025) "Think, Talk, and Design: Exploring the Interplay of Cognition, Communication, and Design Processes." *Journal of Mechanical Design*, **148**(3)
- Ferguson, E. S. (1992) "Engineering and the mind's eye." Cambridge, Mass.: MIT Press
- Finke, R. A. (1989) "Principles of mental imagery." Cambridge, Mass.: MIT Press
- Finke, R. A. (1996) "Imagery, Creativity, and Emergent Structure." *Consciousness and cognition*, **5**(3): 381-393
- Folkmann, M. N. (2014) "Unknown Positions of Imagination in Design." *Design issues*, **30**(4): 6-19
- Goldschmidt, G. & Smolkov, M. (2006) "Variances in the impact of visual stimuli on design problem solving performance." *Design studies*, **27**(5): 549-569
- González, M. A., Campos, A. & Pérez, M. J. (1997) "Mental Imagery and Creative Thinking." *The journal of psychology*, **131**(4): 357-364
- Greene, T., West, M. & Somer, E. (2020) "Maladaptive daydreaming and emotional regulation difficulties: A network analysis." *Psychiatry research*, **285**: 112799
- Hasson, U., *et al.* (2012) "Brain-to-brain coupling: a mechanism for creating and sharing a social world." *Trends in cognitive sciences*, **16**(2): 114-121
- Hay, L., *et al.* (2020) "A novel systematic approach for analysing exploratory design ideation." *Journal of engineering design*, **31**(3): 127-149
- Heylighen, A. & Nijs, G. (2014) "Designing in the absence of sight: Design cognition re-articulated." *Design studies*, **35**(2): 113-132
- Howard, T. J., Culley, S. J. & Dekoninck, E. (2008) "Describing the creative design process by the integration of engineering design and cognitive psychology literature." *Design studies*, **29**(2): 160-180
- Jin, Y. & Chusilp, P. (2006) "Study of mental iteration in different design situations." *Design studies*, **27**(1): 25-55
- Khatena, J. (1975) "Vividness of Imagery and Creative Self Perceptions." *The Gifted child quarterly*, **19**(1): 33-37

- Laurel, B. (2003) "Design research: methods and perspectives." Cambridge, Mass.: MIT Press
- McGown, A., Green, G. & Rodgers, P. A. (1998) "Visible ideas: information patterns of conceptual sketch activity." *Design studies*, **19**(4): 431-453
- Palmiero, M., Cardi, V. & Belardinelli, M. O. (2011) "The Role of Vividness of Visual Mental Imagery on Different Dimensions of Creativity." *Creativity research journal*, **23**(4): 372-375
- Pérez-Fabello, M. J. & Campos, A. (2007) "Influence of Training in Artistic Skills on Mental Imaging Capacity." *Creativity research journal*, **19**(2-3): 227-232
- Peters, M., *et al.* (1995) "A Redrawn Vandenberg and Kuse Mental Rotations Test – Different Versions and Factors That Affect Performance." *Brain and cognition*, **28**(1): 39-58
- Pidgeon, L. M., *et al.* (2016) "Functional neuroimaging of visual creativity: a systematic review and meta-analysis." *Brain and behaviour*, **6**(10): e00540-n/a
- Shealy, T., *et al.* (2020) "Concept generation techniques change patterns of brain activation during engineering design." *Design Science*, **6**
- Shepard, R. N. & Cooper, L. A. (1982) "Mental images and their transformations." Cambridge, Mass.: MIT Press
- Spiller, M. J. & Jansari, A. S. (2008) "Mental imagery and synaesthesia: Is synaesthesia from internally-generated stimuli possible?" *Cognition*, **109**(1): 143-151
- Thomas, N. J. T. (1999) "Are theories of imagery theories of imagination? An active perception approach to conscious mental content." *Cognitive science*, **23**(2): 207-245
- Turner, S. F., Cardinal, L. B. & Burton, R. M. (2017) "Research Design for Mixed Methods: A Triangulation-based Framework and Roadmap." *Organizational research methods*, **20**(2): 243-267
- Vranic, A., Martincevic, M. & Borella, E. (2021) "Mental imagery training in older adults: Which are benefits and individual predictors?" *International journal of geriatric psychiatry*, **36**(2): 334-341

Wang, W. & Duffy, A. H. B. (2009) "A triangulation approach for design research." The Design Society

Wilson, M. (2002) "Six views of embodied cognition" Psychonomic bulletin & review, **9**(4): 625-636

Zeman, A., Dewar, M. and Della Sala, S. (2015) "Lives without imagery – Congenital aphantasia." Cortex, **73**: 378-380

Zhu, W., *et al.* (2017) "Common and distinct brain networks underlying verbal and visual creativity." Human brain mapping, **38**(4): 2094-2111

Appendix 1: Questionnaire distribution pack for Chapter 3

Vividness of Visual Imagery Questionnaire (VVIQ)

Explanation:

The purpose of this test is to provide an approximate measure of the clarity and ability of your mental imagery, also known as the “vividness”. Complete all parts of this questionnaire with your eyes open, then repeat these with your eyes closed, assigning a 1-5 rating for each individual item based on what you perceive, or do not perceive, within your imagery for each one.

Ratings:

- 1 – No image at all, you only “know” that you are thinking of an object
- 2 – Vague and dim
- 3 – Moderately clear and vivid
- 4 – Clear and reasonably vivid
- 5 – Perfectly clear and vivid as normal vision

Theme 1:

Relative or friend

Think of some relative or friend whom you frequently see (but who is not with you at present) and carefully consider the picture that comes before your mind’s eye.

- 1 – The exact contour of face, head, shoulders, and body.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

- 2 – Characteristic poses of head, attitudes of body, etc.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

3 – The precise carriage, length of step, etc. in walking.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

4 – The different colours worn in some familiar clothes.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

Theme 2:

Natural scene: Rising sun

Visualize a rising sun. Consider carefully the picture that comes before your mind's eye.

5 – The sun is rising above the horizon into a hazy sky.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

6 – The sky clears and surrounds the sun with blueness.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

7 – Clouds. A storm blows up, with flashes of lightening.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

8 – A rainbow appears.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

Theme 3:

Shop

Think of the front of a shop which you often go to. Consider the picture that comes before your mind's eye.

9 – The overall appearance of the shop from the opposite side of the road.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

10 – A window display including colours, shape, and details of individual items for sale.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

11 – You are near the entrance. The colour, shape, and details of the door.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

12 – You enter the shop and go to the counter. The counter assistant serves you. Money changes hands.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

Theme 4:

Natural scene: Lake

Think of a country scene which involves trees, mountains, and a lake. Consider the picture that comes before your mind's eye.

13 – The contours of the landscape.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

14 – The colour and shape of the trees.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

15 – The colour and shape of the lake.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

16 – A strong wind blows on the tree and on the lake causing waves.

	1	2	3	4	5
<i>Eyes open</i>					
<i>Eyes closed</i>					

Plymouth Sensory Imagery Questionnaire (PSIQ)

Explanation:

The PSIQ provides an approximate measure for the vividness of mental imagery for varying senses and modalities. Complete all parts of this questionnaire, assigning a 0-10 rating for each item.

Ratings:

0 = no image at all
10 = image as clear and vivid as real life

Imagine the appearance of:

	0	1	2	3	4	5	6	7	8	9	10
<i>A friend you know well</i>											
<i>A cat climbing a tree</i>											
<i>A sunset</i>											
<i>The front door of your house</i>											
<i>A bonfire</i>											

Imagine the sound of:

	0	1	2	3	4	5	6	7	8	9	10
<i>An ambulance siren</i>											
<i>Hands clapping in applause</i>											
<i>The mewling of a cat</i>											
<i>The sound of a car horn</i>											
<i>The sound of children playing</i>											

Imagine the smell of:

	0	1	2	3	4	5	6	7	8	9	10
<i>A stuffy room</i>											
<i>A rose</i>											
<i>Fresh paint</i>											
<i>Newly cut grass</i>											
<i>Burning wood</i>											

Imagine the taste of:

	0	1	2	3	4	5	6	7	8	9	10
<i>Mustard</i>											
<i>Toothpaste</i>											
<i>Lemon</i>											
<i>Sea water</i>											
<i>Black pepper</i>											

Imagine touching:

	0	1	2	3	4	5	6	7	8	9	10
<i>Warm sand</i>											
<i>A soft towel</i>											
<i>The point of a pin</i>											
<i>Icy water</i>											
<i>Fur</i>											

Imagine the bodily sensation of:

	0	1	2	3	4	5	6	7	8	9	10
<i>Relaxing in a warm bath</i>											
<i>Having a sore throat</i>											
<i>Threading a needle</i>											
<i>Jumping into a swimming pool</i>											
<i>Walking briskly in the cold</i>											

Imagine feeling:

	0	1	2	3	4	5	6	7	8	9	10
<i>Excited</i>											
<i>Relieved</i>											
<i>Furious</i>											
<i>In love</i>											
<i>Scared</i>											

Vividness of Movement Imagery Questionnaire (VMIQ)

Explanation:

The VMIQ is similar to the VVIQ but measures mental imagery movement clarity and ability. Complete all parts of this questionnaire for “watching somebody else” first, then repeat for “doing it yourself”, assigning a 1-5 rating for each item.

Ratings:

1 – No image at all, you only “know” that you are thinking of an object

2 – Vague and dim

3 – Moderately clear and vivid

4 – Clear and reasonably vivid

5 – Perfectly clear and vivid as normal vision

1 – Standing

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

2 – Walking

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

3 – Running

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

4 – Jumping

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

5 – Reaching for something on tiptoe

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

6 – Drawing a circle on paper

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

7 – Kicking a stone

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

8 – Bending to pick up a coin

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

9 – Falling forwards

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

10 – Running up stairs

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

11 – Jumping sideways

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

12 – Slipping over backwards

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

13 – Catching a ball with two hands

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

14 – Throwing a stone into water

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

15 – Kicking a ball in the air

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

16 – Hitting a ball along the ground

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

17 – Running downhill

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

18 – Climbing over a high wall

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

19 – Sliding on ice

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

20 – Riding a bike

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

21 – Jumping into water

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

22 – Swinging on a rope

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

23 – Balancing on one leg

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

24 – Jumping off a high wall

	1	2	3	4	5
<i>Watching somebody else</i>					
<i>Doing it yourself</i>					

Mental Rotation Task (MRT)

Explanation:

The MRT is a measure of your ability and speed at rotation set 2D objects. Please follow the instructions at the link below by clicking the link then running the “demo”. Once you have completed the questionnaire a link to the “data” will appear, please click this then screenshot the results and insert them in the space below.

Link:

<https://www.psychtoolkit.org/experiment-library/mentalrotation.html>

Insert results screenshot here:

Style of Processing Questionnaire (SOP)

Explanation:

The SOP questionnaire is a measure of whether your processing style is more visual or verbal. Complete all parts of the questionnaire, providing a rating of 1-4.

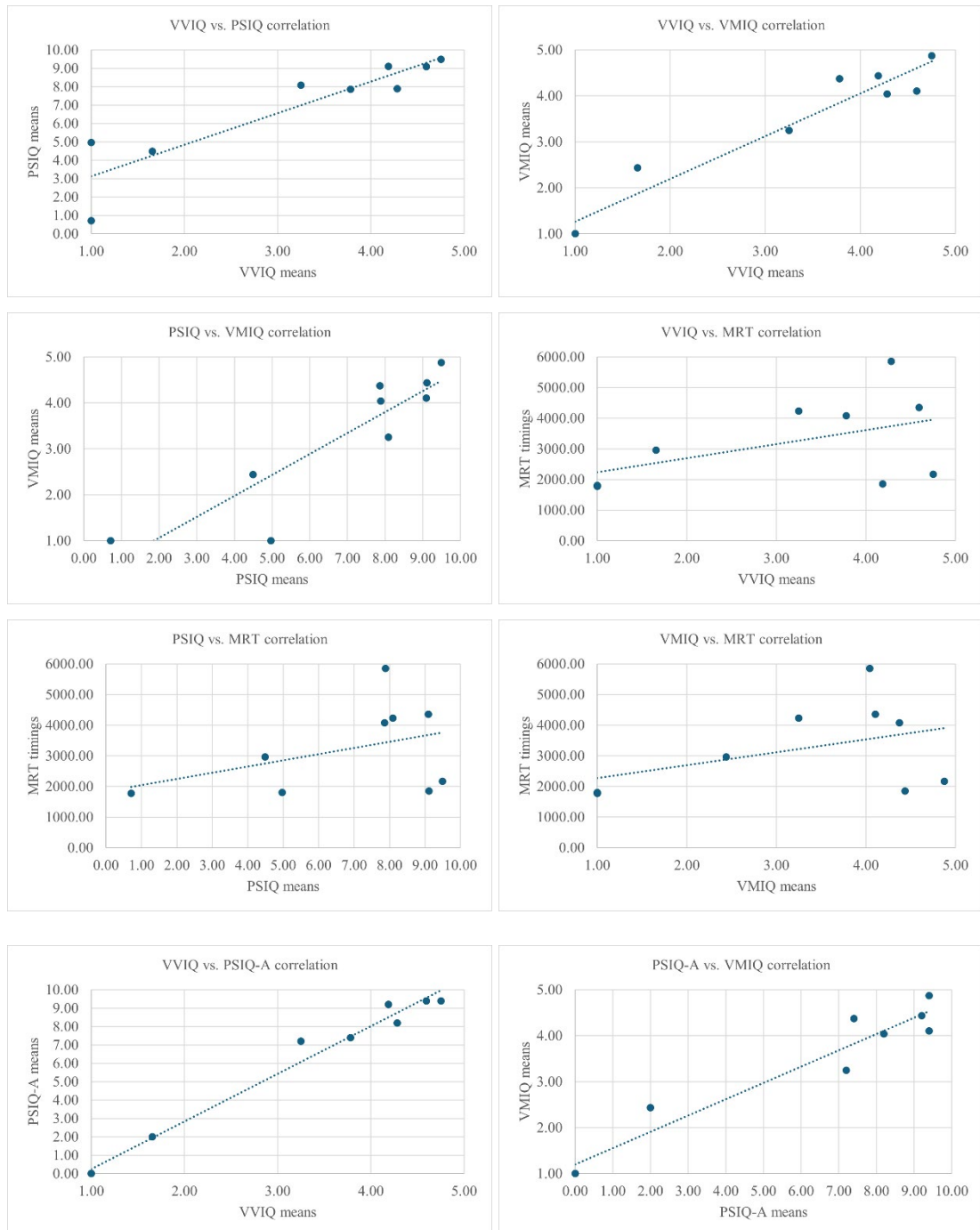
Ratings:

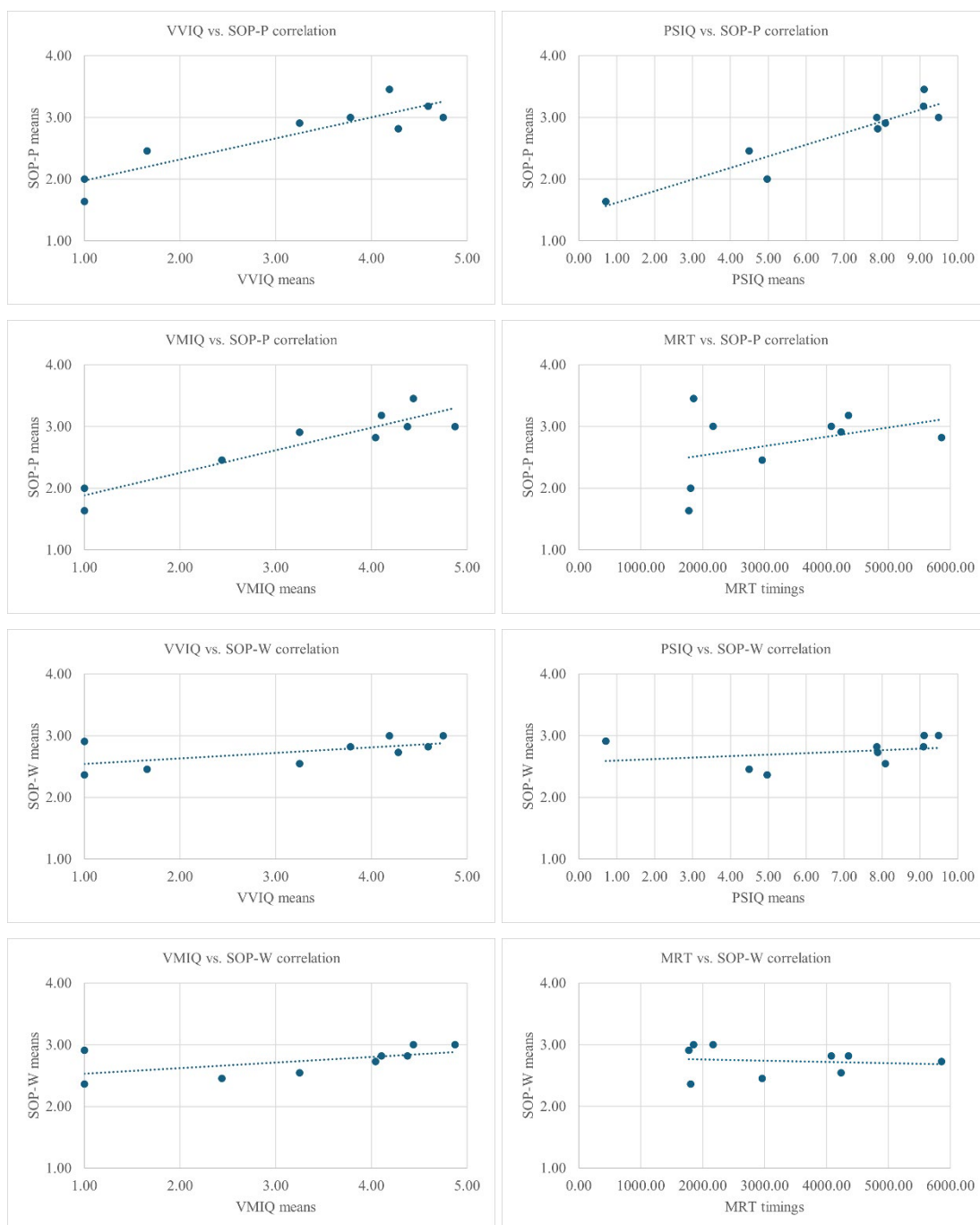
- 1 – always false
- 2 – usually false
- 3 – usually true
- 4 – always true

	1	2	3	4
1. I enjoy doing work that requires the use of words (W)				
2. There are some special times in my life that I like to relive by mentally “picturing” just how everything looked (P)				
3. I can never seem to find the right word when I need it (W)				
4. I do a lot of reading (W)				
5. When I’m trying to learn something new, I’d rather watch a demonstration than read how to do it (P)				
6. I think I often use words in the wrong way (W)				
7. I enjoy learning new words (W)				
8. I like to picture how I could fix up my apartment or a room if I could buy anything I wanted (P)				
9. I often make written notes to myself (W)				
10. I like to daydream, (P)				
11. I generally prefer to use a diagram rather than a written set of instructions (P)				
12. I like to doodle (P)				
13. I find it helps to think in terms of mental pictures when doing many things (P)				

14. After I meet someone for the first time, I can usually remember what they look like, but not much about them (P)				
15. I like to think of synonyms for words (W)				
16. When I have forgotten something I frequently try to form a mental “picture” to remember it (P)				
17. I like learning new words (W)				
18. I prefer to read instructions about how to do something rather than have someone show me (W)				
19. I prefer activities that don’t require a lot of reading (W)				
20. I seldom daydream (P)				
21. I spend very little time attempting to increase my vocabulary (W)				
22. My thinking often consists of mental “pictures” or images (P)				

Appendix 2: Chapter 3 correlation graphs between questionnaires





Appendix 3: Interview questions for Chapter 3

Interview questions/prompts:

Explanation of mental imagery:

The experience of perceiving an image within one's own mind as if experiencing a physical sensation, i.e. visualising within the mind's eye.

Check interviewees understanding of mental imagery

Explanation of mental imagery experiences:

Mental imagery differs from person-to-person: vividness, spatial ability, memory vs imagination behaviours, multisensory imagery and emotional imagery, daydreaming abilities

Interviewees personal experience of mental imagery

Vividness, spatial and rotational ability, colour, etc.

Daydreaming, memory vs imagination, etc.

Multisensory, emotion, etc.

Explanation of mental imagery in design:

It is assumed that mental imagery is of high importance to design but this is not necessarily true for everyone and is highly dependent on your personal experience, i.e. for me

Interviewees experience of mental imagery in how they design

Processes, methods, tools, etc.

Awareness, intention, inspiration, etc.

Changes, fixation, communication, etc.

Extra topics:

- How would you describe taking a mental image and putting it out in the real world?
- Can you draw mental imagery?

Appendix 4: DM300 assessment criteria

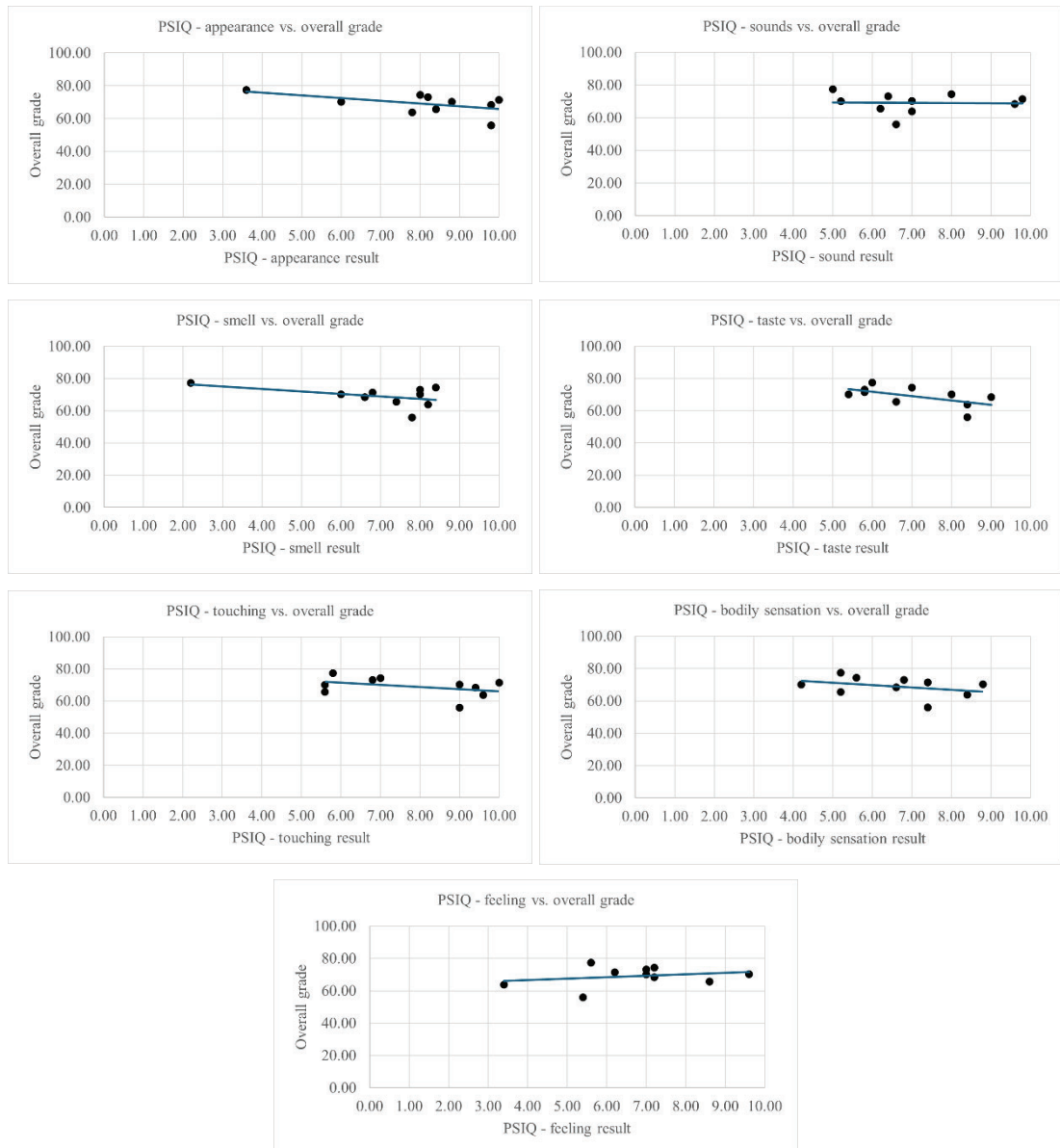
Level of Aesthetic Definition Description for students This aspect relates to the extent to which aesthetics have been considered and developed within the design. Aesthetics are "principles" of what could be perceived the as the "beauty" of the design i.e. what have been the deliberate steps taken to engage people in the design beyond the functionality and the basic ideas of the design. We do not mean that the design must aim to be "beautiful" against some subjective standard, as something that aims to be grotesque could have a high level of aesthetic consideration and the beauty in this case would be the level of care taken to achieve this. For example, the aesthetic of a real bear may create fear in people due to the associations with power, strength and unpredictability of wild animals. It wouldn't be a bad idea to explore the aesthetics of a bear in producing a product that might evoke a primal fear in the user, but there is considerable work in making this an aesthetic that is not simply a replica or caricature of a bear; something that a defined user group would want in their home. There may be a concern that assessors will base their assessment of this element on their on tastes, however the assessment is placed on the evidence abstraction, morphology, synergy and effort in the development of the final form aesthetics. There should not be excessive annotation on the sheets regarding this aesthetic journey (we should see this explanation in the the design journal) rather it should be clear from the form itself. Description for Markers Maximum score 20
Precision of final design form through 3D modelling (digital and physical modelling) Description for students With the aesthetic established the form is required to be detailed. Aspects such as material choice, surface texture, colour precision will cut across both aesthetics and form detailing. The more distinct aspects of the form precision elements will be the inclusion of specific features e.g. the choice of X elements over any other number of elements, positioning of casing splits/buttons/displays/speaker elements, choices in curvature and transition from on form feature to another. Dimensions can be included to convey the precision in the geometry. Description for Markers Maximum score 20
Integrity of experience design framework Description for students We are looking for a synergy between the product form design and all elements of UX. e.g. where consumers will first see and then acquire the product, the vision of the living spaces that the product will be used in, the brand identity and values - how does this all go together with emotional theme? Whilst billboards and bus stop advertising is an easy opportunity for your graphics, does this fit well with the product type and the brand you have presented? Description for Markers Maximum score 20
Quality of visual and made communication Description for students How have the pages been set out well? Are page element carefully considered? Is it easy to follow the layout and understand what is being presented? Are the graphics high resolution and logical in colour choice, font, borders and frames? Has effective use been made of sketches and renders to communicate the design? Is the physical model of a high quality and an accurate reflection of the design? Description for Markers Maximum score 20
Level of critical thinking Description for students Do we see acknowledgement of where the product will undoubtedly be drawing comparisons with other products and aesthetics and presenting something new? Do we see deep and critical thought in where the design came from and how it ended up or could there have been more done to get away from obvious or cliched concepts? Is there a message in theme of the design that reflects what is happening or has happened in the world/ market? Description for Markers Maximum score 20
Expression of reflective critical and individual approach to project Description for students We hope to see evidence of engagement with a broad range of reading (books, papers, magazines, stories, poetry, lyrics), media (film, radio, podcasts, art, photography, architecture, graphic design), sources of inspiration from nature, other products/artifacts/buildings/environments/cultures, your own experiences, phrases you grew up with that have been unpicked and explored more deeply than before. There will be things that did not evolve into solid design ideas and were dropped - this does not need to be explained why not - but we do hope to see a thread emerge from your exploration and be refined over the course of the project. Description for Markers Maximum score 50
Engagement with emotional design and experience design topics and readings Description for students We should see engagement with themes, movements, concepts, philosophies, studies within design. There have been plenty of cues given in the class, you do not need to dissect all of them, or even most of them, but select explore and evidence understanding and use of some. One of the core transitions of the class is to appreciate the history, present and/or future of product design and the role that emotion plays in the connections between designed artifacts and humans. Product design can be perceived as art and/or fashion, and is perhaps neither or both - it can be perceived as relating to timeless classics or to forgettable and disposable items. How have you understood issues like these and used the ideas to position your own product? Fro example you may have started with a concept that was simply described as "old fashioned", but you now understand the precise era and design thinking behind this, and have understood why it is relevant for a new product. Description for Markers Maximum score 50

Appendix 5: Chapter 4 DM300 PSIQ responses

	P1					P2					P3					P4					P5				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
Appearance	9	8	8	8	9	4	5	10	10	10	9	9	8	9	9	10	10	10	10	9	4	5	4	2	3
Sound	7	6	9	7	2	9	10	2	8	6	8	8	7	7	5	6	9	6	6	6	6	7	4	5	3
Smell	5	6	8	9	9	6	10	7	8	10	9	6	8	8	9	7	5	9	8	10	2	1	3	2	3
Taste	8	9	4	7	5	5	9	10	10	8	8	7	8	9	8	9	9	7	7	10	3	7	6	8	6
Touching	6	4	5	6	7	10	9	10	9	10	9	9	9	9	9	9	8	9	9	10	3	5	6	8	7
Bodily sensation	8	8	2	5	3	6	7	10	9	10	9	9	9	7	10	8	8	3	10	8	7	5	3	4	7
Feeling	9	9	8	9	8	1	5	2	4	5	10	10	10	10	8	8	8	4	5	2	5	4	7	5	7

	P6					P7					P8					P9					P10				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
<i>Appearance</i>	10	9	10	10	10	7	8	9	9	7	8	7	7	4	4	7	10	7	10	7	10	10	10	10	10
<i>Sound</i>	8	10	10	10	10	6	9	10	8	8	4	6	5	7	4	5	8	5	5	9	9	10	10	10	10
<i>Smell</i>	7	6	6	7	7	7	9	10	8	8	2	7	8	7	6	5	9	10	10	6	5	6	8	8	7
<i>Taste</i>	10	10	8	10	7	6	8	8	8	5	3	7	6	6	5	3	8	8	5	5	2	7	7	8	5
<i>Touching</i>	10	10	7	10	10	7	7	8	6	7	9	6	4	3	6	5	8	8	5	8	10	10	10	10	10
<i>Bodily sensation</i>	7	7	5	7	7	4	5	7	5	7	5	3	3	6	4	9	3	9	8	5	9	1	8	9	10
<i>Feeling</i>	8	8	8	5	7	6	7	7	8	8	5	6	8	8	8	7	7	9	3	9	8	8	3	10	2

Appendix 6: Chapter 4 PSIQ versus overall grade correlation graphs



Appendix 7: ICED 2023 conference paper

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED23
24-28 JULY 2023, BORDEAUX, FRANCE



A FRAMEWORK FOR UNDERSTANDING MENTAL IMAGERY IN DESIGN COGNITION RESEARCH

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ABSTRACT

Mental imagery is the experience of perceiving an object within one's own mind and is a subjective experience, leading to difficulties in the research and understanding of the phenomenon. This paper documents the development and verification of a framework for researching the elements of mental imagery. The framework was developed following a review of both psychology and design literature which signified three fundamental conceptual viewpoints of mental imagery: imagery modalities, dimensions of imagery ability, and imagery processes. The aim of this framework is to allow for structured research on mental imagery in any given research field. This is verified through discussion for the product design engineering discipline and provides a base for future work on this topic. The conclusions made in this paper reveal that mental imagery, and particularly visual mental imagery, is largely considered to be integral in design overlooking the different realities of designers and confirming a greater need to understand mental imagery experiences in product design engineering.

Keywords: Mental imagery, Design cognition, Creativity, Design process

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Cite this article: Macfie, R. L., Hay, L. A., Rodgers, P. (2023) 'A Framework for Understanding Mental Imagery in Design Cognition Research', in *Proceedings of the International Conference on Engineering Design (ICED23)*, Bordeaux, France, 24-28 July 2023, DOI:10.1017/pds.2023.18

ICED23

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<https://doi.org/10.1017/pds.2023.18> Published online by Cambridge University Press

1 INTRODUCTION

Mental imagery is the experience of visually, or with another sense, perceiving an image within one's own mind (Pearson, 2007; Nanay, 2018; Maciel et al., 2021). Whilst there is an abundance of research into the workings of mental imagery, the cognitive function is still not fully understood, due largely to the personal and subjective nature of mental imagery experiences (Richardson, 1991). Whilst research on the phenomenon of mental imagery is largely psychology-based and on psychological conditions (for example post-traumatic stress disorder) (Holmes & Mathews, 2010), it is widely acknowledged that it has significant importance across many other scientific and creative fields (Kozhevnikov et al., 2013) and an almost casual use in day-to-day life for many people (Pearson, 2007; Casakin & Kreitler, 2011).

The design industry spans a large variety of different professions and roles, including that of product design engineering. It is widely assumed that designers rely heavily on mental imagery, in particular on visual mental imagery, and that visual mental imagery is an essential part of design cognition (Hart & Hay, 2022). However, research shows that there are considerable variations in the experience of mental imagery, from different sense imagery (Floridou, Peerdeman & Schaefer, 2022) to differing levels of clarity between individuals (Gallagher, 2019; Zeman, 2021). There are even reports of distinguished animation artists (Gallagher, 2019) and visual artists (Zeman, 2021) reporting that they experience no visual imagery, and while product design engineering is a very different type of design to art and animation, there are similarities in the assumptions made regarding creative professions and visual mental imagery (Hart & Hay, 2022). Despite the evidence, there is a distinct lack of research into how designers use and experience mental imagery in product design engineering, particularly outside of the visual domain.

This paper provides an overview of the development of a framework for researching mental imagery, as well as current literature found to support its use in a product design engineering context. The framework will support structured research on mental imagery which, given the different and interconnecting elements, can be a relatively unstructured topic. Within product design engineering, the framework will allow for necessary discussion and help to find important areas for further research. This will create a basis for future work that considers all elements and viewpoints of a designer's experience of mental imagery within the design process.

2 DEFINING MENTAL IMAGERY IN DESIGN COGNITION RESEARCH

The field of mental imagery research is expansive and ranges from psychological uses for mental imagery (Holmes & Mathews, 2010) to benefits of imagery utilisation in the design industry (Dahl et al., 2001; Goldschmidt, 2007). This paper was developed from a literature review covering mental imagery research in design, with the scope of the literature ranging from psychology to design in order to gain an in-depth understanding of the experience and map out the research available. The literature was sourced using a range of trusted databases and journals covering both the design and psychology domains, and keywords and phrases that related to both psychology and design research. During this literature review it was realised that research on the topic of mental imagery is complex and interconnecting, with wide differences occurring between individual experiences. In order to provide more structure to the review, a framework was developed for researching mental imagery and applied within a design cognition context. Relevant papers were gathered and grouped together by themes and results that they had in common before the final viewpoints were specified. The final collection of papers that have been used were selected and justified based on their importance to the understanding of mental imagery experiences within design. This section provides a brief overview of the neurobiology and psychology of mental imagery to allow for context before detailing the development of the framework.

2.1 An overview of the neurobiology and psychology of mental imagery

It is widely acknowledged that mental imagery involves a complex brain network (Pearson, 2019), with evidence that activated brain regions are dependent on the form of imagery being engaged (Richardson, 1991). For example, neuroimaging revealed that visual mental imagery activates regions in the occipitotemporal cortex and the ventral visual stream within the brain, while the parietal cortex is active during spatial imagery (Dijkstra et al., 2019). Mental imagery is often described as a "perceptual experience" (Maciel et al., 2021) in which the mind behaves as if it is experiencing a physical sense.

Evidence does suggest that the mental imagery activity can result in small physical reactions within the body, such as the pupils dilating or constricting in response to imagining light or dark scenarios and objects, in the same way as looking at a bright light (Laeng & Sulutredt, 2014; Zeman, 2021). It has been determined that other cognitive functions are needed for mental imagery processing due to the complexity of the task, as is discussed further in this paper. The cognitive functions used within mental imagery may differ slightly depending on the task being undertaken, from daydreaming to visual imagination imagery, or even dreaming (Palmiero et al., 2016). For example, Zeman (2021) found that an individual asked to visualise a flower would need to use functions associated with being awake and attentive, whilst daydreaming often does not require someone to be fully attentive. Although mental imagery seems to play an important role in the day-to-day lives of many people (Kozhevnikov et al., 2013), there is still considerable scientific disagreement on what is involved and a number of competing hypotheses and models. This disagreement leads to added complexity in researching the function within design cognition and creates a solid basis for the development of a supportive framework.

2.2 Developing a framework for mental imagery research

Researching a topic as complex and subjective as mental imagery is a difficult task. Each person can have an entirely different experience of imagery, given that it exists entirely within one's own mind (Maciel et al., 2021). Within the development of the framework there are three fundamental conceptual viewpoints of mental imagery are identified. Considering literature from both psychology and design it was determined that these viewpoints consist of **imagery modalities**, the **dimensions of imagery ability**, and **imagery processes**. Imagery modalities consists of the different senses in imagery, as well as the connection and impact of emotion; dimensions of imagery ability are topics such as imagery vividness, spatial ability, and measurements of imagery; and imagery processes involves tasks such as image generation and retention, or the use of memory images. Whilst these can be standalone topics, it is necessary to keep in mind how closely they all interact with each other. For example, dimensions closely interact with modalities in that individuals can have differing levels of vividness across different modalities (Maciel et al., 2021), and memory imagery (process) can impact on emotion and modalities (Taruffi & Küssner, 2019). Figure 1 provides a graphic interpretation of the framework, and depicts the three viewpoints surrounding the main topic, with all viewpoints interconnecting, and then converging back into the centre. This framework has been developed with the expectation that it can be employed to research mental imagery within different fields. Exactly that has been done here for product design engineering, and the remainder of this paper is a discussion of the literature findings as verification of the framework.

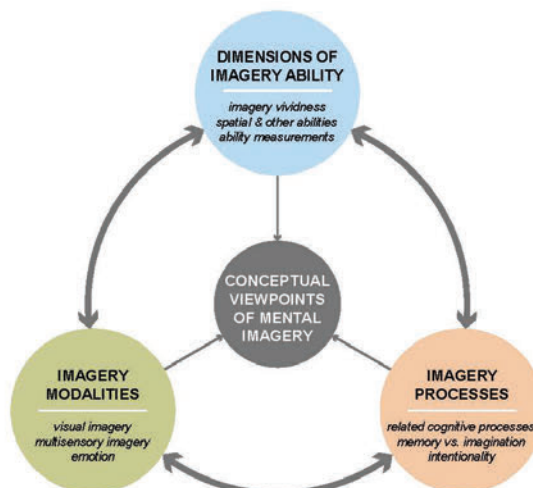


Figure 1: Framework for understanding the multiple viewpoints of mental imagery

3 MENTAL IMAGERY IN PRODUCT DESIGN ENGINEERING

As mentioned, it is regularly assumed that design and mental imagery are consistently closely intertwined (Goldschmidt, 1991; Hart & Hay, 2022). This assumption, however, overlooks that the mental imagery experience can vary greatly between designers, design processes, and design tasks. It has been shown throughout research that designers are capable of creating entirely within the "mind's eye" (Athavankar, 1997) or despite having no experience of mental imagery at all (Gallagher, 2019; Zeman, 2021). Through the framework developed and detailed above, it is possible to analyse the relevant design research, as well as any psychological research that may contain important insights for design.

3.1 Mental imagery modalities

Commonly, mental imagery is believed to be an entirely visual experience, but in reality, it is a multisensory experience activated through the senses and can include auditory, olfactory, tactile and motor function imagery (Goldschmidt, 1994; Maciel et al., 2021). The majority of mental imagery research, particularly within design, focuses on visual imagery, largely disregarding other modalities. One potential reason for this is that it is commonly believed (potentially erroneously) that visual imagery is the most dominant modality that designers use (Bensafi et al., 2012). Whilst visual imagery in particular is useful for problem-solving as it encourages creative thinking and allows for easier simulation both internally and externally (Athavankar, 1997; Bilda et al., 2006; Bilda & Gero, 2008), it would be naive to assume that other modalities do not have use in design.

3.1.1 Visual imagery

Visual mental imagery, often referred to as "visual thinking", "visual perception" or "visualisation" (Goldschmidt, 1994; Dahl et al., 2001; Kavakli & Gero, 2001; Zeman, 2021) refers to the act of "seeing" within the so-called "mind's eye". It refers to a task that is similar to visual perception (Cui et al., 2007), and is often triggered by information obtained from a stimulus other than a visual representation itself (Kosslyn, Behrmann & Jeannerod, 1995), for example music can trigger visual memories (Taruffi & Küssner, 2019). Often, visual mental imagery consists of a remembered image, either in its initial form or as a modification of remembered information (Taruffi & Küssner, 2019).

In neurobiological terms, there is evidence to suggest that mental imagery and visual perception rely on similar neural mechanisms within the brain (Dijkstra et al., 2017; Dijkstra et al., 2019) and that impacts on visual perception can also impact on mental imagery (Pearson et al. 2011). An example may be found in the binocular rivalry paradigm (Dijkstra et al., 2019). Binocular rivalry describes the visual fight for perceptual dominance that occurs when a person is shown two differing images at one time. In terms of mental imagery, there is evidence that if an observer mentally visualises one of the images first, it produces a bias whereby this is the image they will likely perceive (described by Dijkstra et al. (2019) as having "a priming effect").

Whilst mental imagery has been shown to improve both experience and outcome in design, several designers claim to refuse to use it or cannot use it due to reduced vividness (Dahl et al., 1999; Dahl et al., 2001). Gallagher (2019) provided evidence that creative individuals and designers can successfully design despite having low or no visual imagery, and so it can be deduced that the assumption that mental imagery is key to design (Bildá & Gero, 2008) is not necessarily correct.

3.1.2 Multisensory imagery

As noted earlier, mental imagery can occur in each of the senses and measuring such will be discussed further in this report. Whilst an individual can experience all forms of imagery, it is also possible for them to experience differing variations, for example one may experience high levels of imagery in every modality except visual (Maciel et al., 2021). Multisensory imagery has a vast range of applications, including psychological treatments, such as auditory imagery in cognitive behavioural therapy (CBT) (Nanay, 2018). There is also evidence that physical sensory practice has immense effects on imaging ability: musicians tend to outperform non-musicians in auditory vividness questionnaires, and perfumers have stronger reported olfactory imagery than the general public (Bensafi et al., 2012). Whilst research into the impact of multisensory imagery in design is extremely limited, it is interesting to consider whether there is a significance to some of these findings within a design setting, such as theorising if designers have stronger visual imagery because they are trained in a largely visual setting.

3.1.3 Emotion and mental imagery

Research provides strong links between emotion and mental imagery, and suggests that trait empathy differences are linked to higher levels of imagery (Taruffi & Küssner, 2019). Mental imagery often has a greater emotional impact than verbal interpretations of potential future situations as it allows for “pre-experiencing” of said situations (Ji et al., 2022) and there is evidence that mental imagery plays a key role in emotional and psychiatric disorders and treatments (Holmes & Mathews, 2010). Additionally, there is physical evidence that fear imaging produces a stronger response than neutral situational imaging in that, for example, fearful mental imagery has been shown to cause an increased heart rate (Holmes & Mathews, 2010). As discussed, multi-sensory mental imagery appears to mimic multi-sensory perception in those that are capable of the experience and evidence suggests that emotional imagery works in the same way. For example, if an individual has a phobia of snakes, using mental imagery to visualise a snake approaching would cause a similar emotional response as physically watching a snake approach (Holmes & Mathews, 2010). Additionally, the nature of an image, as well as the emotional capabilities of the individual, will play a role in the impact an image has; there is evidence that the more vivid visual imagery a person experiences, the more intense and emotional any imagined future events are (D’Argembeau & Van der Linden, 2006, Holmes & Mathews, 2010). Within a design context, evidence shows that if a designer visualises the customer use of a product, it can increase the level of empathy featured in the design process and lead to a greater understanding of the customer’s perspective (Dahl et al., 2001).

3.2 Dimensions of imagery ability

The mental imagery experience is different for each individual and is not one-size-fits-all, with individuals experiencing mental imagery at varying ability and clarity (Kavakli & Gero, 2001). Mental imagery is a largely personal experience and therefore subjective (Richardson, 1991) and while differences can occur across different modalities, the research on dimensional abilities largely refers to visual imagery.

3.2.1 Mental imagery vividness

The spectrum of mental imagery clarity is normally referred to as the “vividness” of mental imagery. Individuals report anywhere from a complete lack of mental imagery to extremely vivid mental imagery (Cui et al., 2007; Kozhevnikov et al., 2013; Pearson, 2019; Bainbridge et al., 2021; Zeman, 2021), though the research primarily covers clarity or vividness differences in the visual modality. Whilst differences in visual imagery vividness have been discussed for decades, it was only in 2015 that the extremes of aphantasia and hyperphantasia were named by Professor Adam Zeman (Bainbridge et al., 2021; Zeman, Dewar & Della Sala, 2015). Aphantasia is the complete lack of visual mental imagery (Gallagher, 2019; Zeman, Dewar & Della Sala, 2015), while hyperphantasia describes imagery so vivid it can be similar to a physical sensation (Bainbridge et al., 2021). Aphantasia affects roughly 1-3% of people, although most adults knowingly living with aphantasia do not realise it exists until they are into adulthood (Rhodes, 1981), whilst hyperphantasia affects around 3-7% (Zeman, 2021). Milton et al.’s (2021) studies suggest people with hyperphantasia perform better in memory tests, whilst people with aphantasia tend to be less extraverted and open than those with hyperphantasia. Despite the lack of visual mental imagery, aphantasia does not usually have a negative impact on life experience (Bainbridge et al., 2021) nor does it necessarily impact on creative abilities (Gallagher, 2019; Zeman, 2021).

3.2.2 Spatial and other abilities

According to Allan (2010), the components of imagery spatial ability include mentally seeing in 2-dimensions (2D) within a 3-dimensional (3D) environment, mentally rotating objects, and mentally seeing objects in scale within mental imagery. There is evidence that while those with diagnosed or self-diagnosed aphantasia consistently score as such on visual imagery tests, they tend to still score highly on mental rotation and spatial ability tests (Keogh & Pearson, 2018). This implies potentially separate functions for different abilities, but there is a lack of further research into this occurrence. Mental scanning is a task where an individual perceives, within imagery, moving from one point to another, usually engaging visual imagery (Gallace, 2012). Another example of a difference in dimensional ability is the timing for mental rotation (Pearson et al. 2011) and the speed at which individuals manipulate or process images within their mind: there is evidence that the more mental

rotation that a task requires, the longer said task will take (Kosslyn, Behrmann & Jeannerod, 1995). Researchers in mental rotation differences tend to rely heavily on theories of embodied cognition and suggest that this plays a role in differences (Voyer et al., 2020). Whilst standard definitions perceive cognition as a computational activity with the brain performing the operation alone, embodied cognition provides a more complex and inclusive view (Tedjaputro & Shih, 2019). Embodied cognition views thinking as an active relationship between the body, the mind and the surrounding environment, where cognition is the body's interaction with the world (Tedjaputro & Shih, 2019).

3.2.3 Measurement systems

Measurement systems have been developed across the field of mental imagery psychology research as a way of quantifying the different imagery experiences. The most common method of measurement within psychology are written or verbal self-report questionnaires. One example of these questionnaires are spatial or mental rotation ability tests which use pictorial questions to ask the responder to match up rotated images (Peters et al., 1995). Whilst the exact nature, appearance and content of visual mental imagery is difficult to measure, the Vividness of Visual Imagery Questionnaire (VVIQ), first developed by psychologist David Marks in 1973 (Bainbridge et al., 2021), is a written questionnaire designed to provide a way to measure vividness of mental imagery through scenario-style questions (Kozhevnikov et al., 2013; Zeman, 2021). Further questionnaires have been created in an attempt to quantify multisensory imagery vividness, such as the Plymouth Sensory Imagery Questionnaire (PSI-Q), which was developed to measure appearance, sound, smell, taste, bodily sensation, feeling and touch imagery (Andrade et al., 2014). In psychology, so-called "social desirability measurements" have been suggested to minimise the subjective nature of mental imagery questionnaires. Social desirability scales are a psychological measure that were designed to test whether individuals answer self-response tests in what is seen as a culturally approved way by presenting questions and scenarios that intend to describe improbable or negative behaviours (Holtrop et al., 2021). It is believed that if a person responds to many of these claims in a way that depicts them as an overly virtuous person, they are more than likely lying or answering in what they deem to be a socially desirable way (Holtrop et al., 2021).

Whilst still lacking in evidence, other measures of imagery vividness have been suggested which could provide a more objective form of measurement (Bainbridge et al., 2021). According to Cui et al. (2007), it is possible that the vividness individuals experience is directly linked to the activity of their visual cortex, and it has been suggested that there could be a way to develop a method using modern technology, for example fMRI, which tracks and measures the visual cortex. There is further evidence in Pearson, Rademaker and Tong (2011) which shows that subjective vividness ratings can predict level changes in the visual cortex during mental imagery. More recently, there has been evidence that pupil response may be an appropriate measure of aphantasia. Hawley's (2022) work has shown that when asked to mentally visualise a light versus a dark image, the pupils of people living without aphantasia respond as they would to visually seeing a light versus a dark object, whereas in people living with aphantasia, there is no pupil response when asked the same.

Measurement systems for mental imagery within design itself are lacking, but one method for understanding experiences during design tasks is protocol analysis. Protocol analysis is a psychological method that comes under the banner of self-reporting and allows for the analysis of mental processes through verbal reports (Hay et al., 2017; Lawrie, Hay & Wodehouse, in press). In design research, protocol analysis is undertaken through visual and audio recordings of a designer either during or after a design task, following which the recordings are coded and analysed according to a coding scheme (Gero & McNeill, 1998; Hay et al., 2017; Lawrie, Hay & Wodehouse, in press). The recordings can include verbal responses, sketches, and actions (Hay et al., 2017). Although the high level of data gathered in protocol studies makes it a very time-consuming analysis method, the detailed insight into the internal process of a designer, which is a subjective experience, makes it a popular method in design research (Hay et al., 2017).

3.3 Mental imagery processes

Mental imagery processes, meaning the imagery actions and tasks undertaken by an individual, can take many different forms and styles, from the generation, transformation and inspection of imagery (Rademaker & Pearson, 2012) to perceptual or active imagery (Kavakli & Gero, 2001). Kosslyn, Behrmann and Jeannerod (1995) suggest that mental imagery involves a number of working processes that include forming, scanning, interpreting, maintaining and transforming images. In the same

literature, mental imagery processes are grouped into four categories: learning and memory, perception and action, information processing, and reasoning using imagery (Kosslyn, Behrmann & Jeannerod, 1995). The term “interactive imagery” has been used to describe the task of refining and transforming images within the mind due to the ease at which individuals can interact with and manipulate the shapes (Goldschmidt, 1991). The experience of mental imagery itself allows individuals to access thoughts, senses, and emotions entirely within their mind and provides a strong base for creating new ideas (Palmiero et al., 2016).

One often discussed difference in mental imagery processes are the clear distinctions between memory imagery and imagination imagery (Rhodes, 1981; Dahl et al., 1999; Dahl et al., 2001; Pearson, 2007; Pearson, 2019). Whilst mental imagery can include the creation of new, “imagined” ideas and images, it can also be as simple as remembering an image or idea that has already been defined within memory (Dahl et al., 1999; Dahl et al., 2001; Kavakli & Gero, 2001). Different imagery processes can impact on problem-solving in design: memory imagery allows the designer to draw from their own experiences and knowledge to design a product, whilst imagination imagery can allow them to create more novel ideas (Dahl et al., 1999; Dahl et al., 2001). Evidence suggests most designers will automatically begin by focusing on memory imagery before moving to imagination imagery, if they are capable, likely due to it being simpler to start from something they know and have experienced (Dahl et al., 2001). For this reason, it is somewhat unsurprising that Gero and Milovanovic (2020) found that designers who are experienced in their fields tend to think and work faster and more intuitively than novice designers. Whilst both memory and imagination imagery are described as useful for the design process, imagination imagery has been suggested as more efficient for product ideation as it appears to allow for a more novel product (Dahl et al., 1999; Herd & Mehta, 2019).

One way in which we can discuss imagery use is through intentionality and whether mental imagery is experienced voluntarily, meaning an individual can willingly call up images within their mind, or involuntarily, such as whilst experiencing intrusive thoughts (Floridou, Peerdeman & Schaefer, 2022). There is a simplicity that comes with using mental imagery in design (Goldschmidt, 2007) due to the potential reduction in tools needed and the ease with which new ideas can be generated. Furthermore, as design is heavily dependent on context (Goldschmidt, 2007), evidence suggests that a designer’s experience of visual imagery during the design process can have a big impact on both the novelty and usefulness of the final design (Dahl et al., 2001). Additionally, the transformation from mental imagery to physical visualisation creates a form of balance between fantasy and reality that allows for more creative and novel designs (Allen, 2010). However, evidence suggests that experienced designers are still reluctant to take full advantage of the experience of mental imagery to assist them in design, or so they claim (Dahl et al., 2001). It is possible that this could be explained by intentionality: if a designer assumes that their mental imagery is an involuntary or expected part of the design process, we can theorise that they may be overlooking the potential power of voluntarily creating new ideas within their so-called mind’s eye.

There are different steps within mental imagery according to Casakin and Kreidler (2011), and designers alternate between “framing”, “making moves” and “evaluating moves” during the design process to navigate their way through problem-solving. An important point raised by Bilda and Gero (2008), is that whilst design obviously occurs during the design process itself, it can also occur out with the physical design environment, and a designer could find themselves struck with inspiration at another time, for example while travelling from work. Through the phenomenon, a designer can have an idea or a design breakthrough at any time, with inspiration coming from even the smallest places (Bildá & Gero, 2008).

Mental imagery does come with its own set of issues, such as problems stemming from short term memory – if a designer was to create entirely within their own mind, they would be at risk of forgetting and excluding parts of the final design (Athavankar, 1997). One method around this issue is to use mental imagery in conjunction with tools and design methods, such as mind mapping, which in itself is a method that relies heavily on imagery and the fast processing of ideas within the mind (Athavankar, 1997; Bildá & Gero, 2008). Techniques such as this encourage the designer to look for creative solutions within their own skill base and knowledge (Allen, 2010). As mentioned throughout this paper, the use of mental imagery is an entirely internal process, meaning that designers live within their own catalogue of images and design can rely on the interaction between this internal process and external processes, such as sketching (Athavankar, 1997; Bildá & Gero, 2008; Tedjosaputro et al., 2014). Most designers would argue that sketching is an essential step in the design process

(Athavankar, 1997) and it is a simple yet reliable method of communication and reasoning which encourages the development of ideas (Goldschmidt, 1991; Bilda & Gero, 2008; Tedjosaputro et al., 2014). Sketching is particularly useful within design teams as it increases communication by allowing ideas and images to be shared more easily (Goldschmidt, 2007).

4 CONCLUSIONS

The literature review conducted for this paper provided insight into how mental imagery can be successfully researched within the context of product design engineering. It allowed the development of a framework breaking down the elements involved in mental imagery research. It was found that mental imagery can be split into three conceptual viewpoints that can be viewed interconnectedly with each other: imagery modalities, dimensions of imagery ability, and imagery processes. Whilst this research is limited by the amount of literature on the topic in product design engineering specifically, it was found that psychology research and design research in other domains, such as architecture, could have relevance to the field of product design engineering.

Mental imagery itself is a personal experience with designers able to manipulate the ideas within their minds (Athavankar, 1997; Oxman, 2002). The subjective nature of the experience leads to different definitions and understandings. This is a particular issue in a field such as design, where individuals are strongly believed to need mental imagery to thrive (Hart & Hay, 2022). In this paper, the framework presented in Figure 1 was used to structure the literature on mental imagery from across the design and psychology fields. This has allowed a greater insight into the aspects of the mental imagery experience that should be considered when researching the topic in the product design engineering context, as well as providing evidence of the different experiences of mental imagery (Gallagher, 2019; Zeman, 2021). The use of the framework in respect to product design engineering alongside further work on this topic should allow for a definition of mental imagery within the field to emerge.

An important detail of the framework that should be considered during mental imagery research is that each of the viewpoints interact with each other. It is difficult to consider one element of mental imagery without keeping the others in mind, particularly when considering how it is experienced within product design engineering. An example of this is that Maciel et al. (2021) found that it is possible that individuals can experience differing levels of mental imagery vividness for different modalities. Given the varying experiences of visual mental imagery in design (Gallagher, 2019), it is feasible that different designers use different sensory perception at different levels. Additionally, Dahl, Chattopadhyay and Gorn (1999; 2001) found that intentionally utilising mental imagery within the design process by way of visualising the end user of a product provides a designer with a greater sense of empathy, leading to more useful final products. Given that there is an intricate connection between emotion or empathy and imagery (Taruffi & Küssner, 2019), it is feasible that there is a link between intentionality of mental imagery (process) and emotion or empathic ability in design (modality).

This review has uncovered important literature on the experience of mental imagery in product design engineering. However, there is a significant lack of research on the topic within the relevant field, leading to questions about how mental imagery is experienced and if it can be better utilised to create stronger solutions. Given that there is still a strong assumption that design and mental imagery are inherently connected but that there is evidence suggesting this is not the case (Gallagher, 2019; Zeman, 2021), it is worth considering that important aspects are being overlooked. For example, can a designer choose which imagery modality to use during design, or are they able to train their intentionality? For this reason, it is evident that this framework can be used further in potential studies as a way of considering the aspects that may impact a designer's experience, use or understanding of their own mental imagery during the design process.

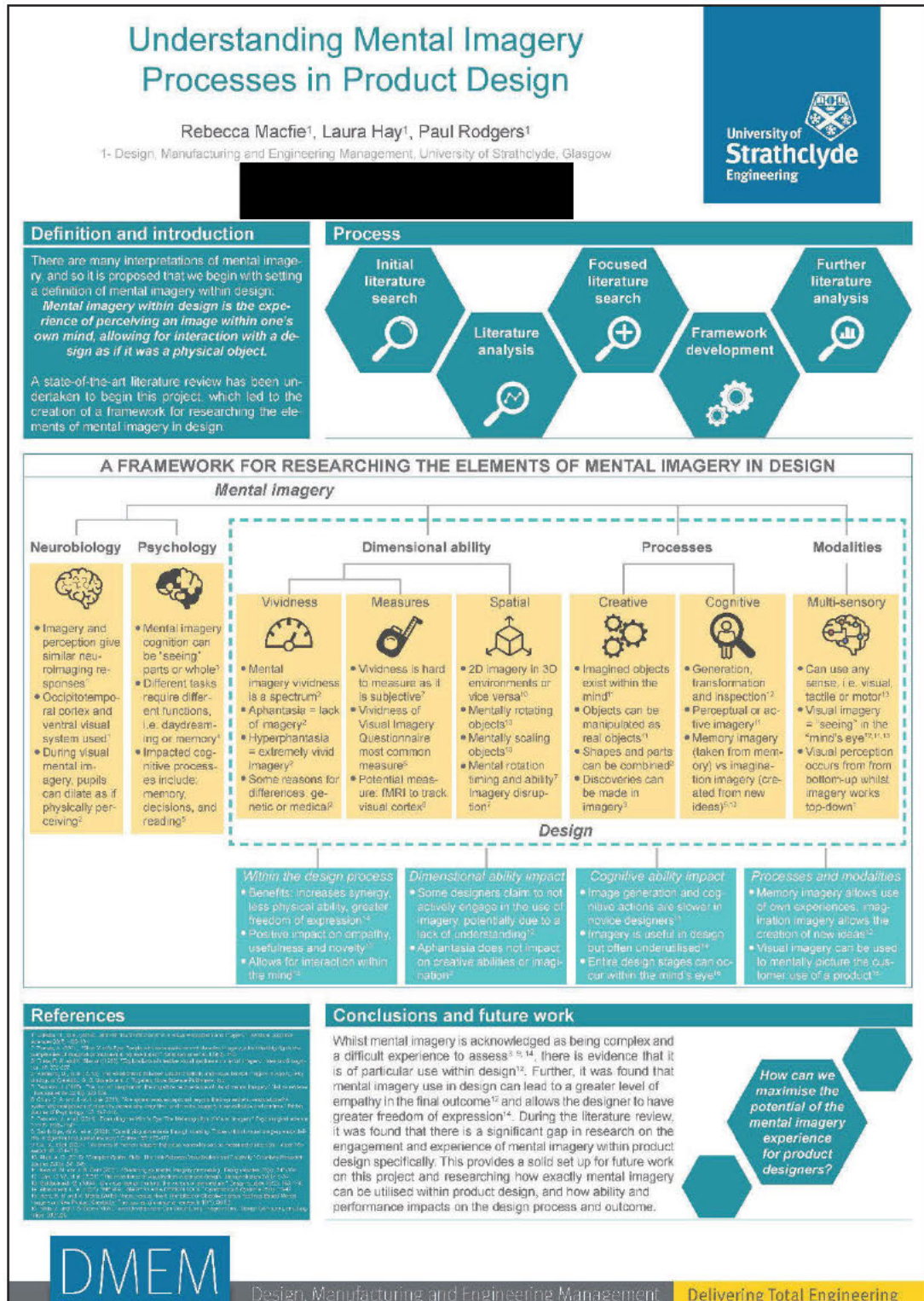
REFERENCES

- Allen, A.D. (2010) Complex Spatial Skills: The Link Between Visualization and Creativity, *Creativity Research Journal*, 22(3), pp.241-249.
- Andrade, J., et al. (2014) Assessing vividness of mental imagery: The Plymouth Sensory Imagery Questionnaire, *The British journal of psychology*, 105(4), pp.-547-563.
- Athavankar, U.A. (1997) Mental Imagery as a Design Tool, *Cybernetics and systems*, 28(1), pp.25-42.
- Bainbridge, W.A. et al. (2021) Quantifying aphantasia through drawing: Those without visual imagery show deficits in object but not spatial memory, *Cortex*, 135, pp.159-172.

- Bensafi, M. et al. (2012) Olfactory and Gustatory Mental Imagery: Modulation by Sensory Experience and Comparison to Auditory Mental Imagery, in *Multisensory Imagery*. New York, NY: Springer New York, pp.77-91.
- Bilda, Z., Gero, J.S. and Purcell, T. (2006) To sketch or not to sketch? That is the question, *Design studies*, 27(5), pp.587-613.
- Bilda, Z. and Gero, J.S. (2008) Idea Development Can Occur Using Imagery Only, *Design Computing and Cognition '08*, pp.303-320.
- Casakin, H. and Kreidler, S. (2011) The cognitive profile of creativity in design, *Thinking skills and creativity*, 6(3), pp.159-168.
- Cui, X. et al. (2007) Vividness of mental imagery: Individual variability can be measured objectively, *Vision research (Oxford)*, 47(4), pp.474-478.
- D'Argembeau, A. and Van der Linden, M. (2006) Individual differences in the phenomenology of mental time travel: The effect of vivid visual imagery and emotion regulation strategies, *Consciousness and cognition*, 15(2), pp.342-350.
- Dahl, D.W., Chattopadhyay, A. and Gorn, G.J. (1999) The use of visual mental imagery in new product design, *Journal of marketing research*, 36(1), pp.18-28.
- Dahl, D.W., Chattopadhyay, A. and Gorn, G.J. (2001) The importance of visualisation in concept design, *Design studies*, 22(1), pp.5-26.
- Davis, J.I. et al. (2012) Four Applications of Embodied Cognition, *Topics in cognitive science*, 4(4), pp.786-793.
- Dijkstra, N. et al. (2017) Distinct top-down and bottom-up brain connectivity during visual perception and imagery, *Scientific reports*, 7(1), pp.5677-9.
- Dijkstra, N. et al. (2019) Between-subject variability in the influence of mental imagery on conscious perception, *Scientific reports*, 9(1), pp.15658-10.
- Dijkstra, N., Bosch, S.E. and van Gerven, M.A.J. (2019) Shared Neural Mechanisms of Visual Perception and Imagery, *Trends in cognitive sciences*, 23(5), pp.423-434.
- Floridou, G.A., Peerdeman, K.J. and Schaefer, R.S. (2022) Individual differences in mental imagery in different modalities and levels of intentionality, *Memory & cognition*, 50(1), pp.29-44.
- Gallace, A. (2012) Somesthetic Mental Imagery, in *Multisensory Imagery*. New York, NY: Springer New York, pp.29-50.
- Gallagher, J. (2019) Aphantasia: Ex-Pixar chief Ed Catmull says 'my mind's eye is blind', *BBC News*: <https://www.bbc.co.uk/news/health-47830256>, accessed 14:15 03/11/2022.
- Gero, J.S. and Milovanovic, J. (2020) A framework for studying design thinking through measuring designers' minds, bodies and brains, *Design Science*, 6.
- Goldschmidt, G. (1991) The dialectics of sketching, *Creativity research journal*, 4(2), pp.123-143.
- Goldschmidt, G. (1994) On visual design thinking: the vis kids of architecture, *Design studies*, 15(2), pp.158-174.
- Goldschmidt, G. (2007) To see eye to eye: the role of visual representations in building shared mental models in design teams, *CoDesign*, 3(1), pp.43-50.
- Hart, E. and Hay, L. (2022) Do you see what I see? Exploring vividness of visual mental imagery in product design ideation, *Proceedings of the Design Society*, 2, pp.881-890.
- Hawley, J. (2022) Windows to the soul: Pupils reveal 'aphantasia', the absence of visual imagination, *UNSW Newsroom*: <https://newsroom.unsw.edu.au/news/science-tech/windows-soul-pupils-reveal-aphantasia-absence-visual-imagination>, accessed 14:17 03/11/2022.
- Hay, L. et al. (2017) A systematic review of protocol studies on conceptual design cognition: Design as search and exploration, *Design Science*, 3.
- Herd, K.B. and Mehta, R. (2019) Head versus Heart: The Effect of Objective versus Feelings-Based Mental Imagery on New Product Creativity, *The Journal of consumer research*, 46(1), pp.36-52.
- Holmes, E.A. and Mathews, A. (2010) Mental imagery in emotion and emotional disorders, *Clinical psychology review*, 30(3), pp.349-362.
- Holtrop, D. et al. (2021) Do social desirability scales measure dishonesty?: A think-aloud study, *European journal of psychological assessment*: official organ of the European Association of Psychological Assessment, 37(4), pp.274-282.
- Ji, J.L. et al. (2022) Emotional mental imagery generation during spontaneous future thinking: relationship with optimism and negative mood, *Psychological research*, 86(2), pp.617-626.
- Kavakli, M. and Gero, J.S. (2001) Sketching as mental imagery processing, *Design studies*, 22(4), pp.347-364.
- Keogh, R. and Pearson, J. (2018) The blind mind: No sensory visual imagery in aphantasia, *Cortex*, 105, pp.53-60.
- Kosslyn, S.M., Behrmann, M. and Jeannerod, M. (1995) The cognitive neuroscience of mental imagery, *Neuropsychologia*, 33(11), pp.1335-1344.
- Kozhevnikov, M. et al. (2013) Creativity, visualization abilities, and visual cognitive style, *British journal of educational psychology*, 83(2), pp.196-209.

- Laeng, B. and Sulutvedt, U. (2014) The Eye Pupil Adjusts to Imaginary Light, *Psychological science*, 25(1), pp.188–197.
- Lawrie, E., Hay, L. and Wodehouse, A. [In press] A classification of methods and constructs in design cognition research, *Design Computing and Cognition* '22.
- Maciel, I.M. et al. (2021) Mental Imagery for Multisensory Designers: Insights for Non-visual Design Cognition, in *Design for Tomorrow—Volume 1*. Singapore: Springer Singapore (Smart Innovation, Systems and Technologies), pp.109–118.
- Milton, F. et al. (2021) Behavioral and Neural Signatures of Visual Imagery Vividness Extremes: Aphantasia versus Hyperphantasia, *Cerebral Cortex Communications*, 2(2).
- Nanay, B. (2018) Multimodal mental imagery, *Cortex*, 105, pp.125–134.
- Oxman, R. (2002) The thinking eye: visual re-cognition in design emergence, *Design studies*, 23(2), pp.135–164.
- Palmiero, M. et al. (2016) Editorial: Creativity and mental imagery, *Frontiers in psychology*, 7.
- Pearson, D.G. (2007) Mental Imagery and Creative Thought, in *Imaginative Minds*. British Academy (Proceedings of the British Academy).
- Pearson, J. (2019) The human imagination: the cognitive neuroscience of visual mental imagery, *Nature reviews - Neuroscience*, 20(10), pp.624–634.
- Pearson, J., Rademaker, R.L. and Tong, F. (2011) Evaluating the Mind's Eye: The Metacognition of Visual Imagery, *Psychological science*, 22(12), pp.1535–1542.
- Peters, M. et al. (1995) A Redrawn Vandenberg and Kuse Mental Rotations Test - Different Versions and Factors That Affect Performance, *Brain and cognition*, 28(1), pp.39–58.
- Rhodes, J.W. (1981) Relationships Between Vividness of Mental Imagery and Creative Thinking, *The Journal of creative behavior*, 15(2), pp.90–98.
- Richardson, J. (1991) Imagery and the Brain, in *Imagery and Cognition*. New York: Springer-Verlag, pp.1–45.
- Taruffi, L. and Küssner, M.B. (2019) A Review of Music-Evoked Visual Mental Imagery: Conceptual Issues, Relation to Emotion, and Functional Outcome, *Psychomusicology*, 29(2-3), pp.62–74.
- Tedjosaputro, M.A. et al. (2014) Multidisciplinary Design Behaviour Using Sketching and Mental Imagery: A Literature Review and Considerations for Future Research, in *ICoRD'15 – Research into Design Across Boundaries Volume 1*. New Delhi: Springer India (Smart Innovation, Systems and Technologies), pp.27–37.
- Tedjosaputro, M.A. and Shih, Y.-T. (2019) A Visualization Tool to Investigate the Interplay of External and Internal Processes, in *Design Computing and Cognition '18*. Cham: Springer International Publishing, pp.669–686.
- Voyer, D. et al. (2020) Sex Differences in Tests of Mental Rotation: Direct Manipulation of Strategies With Eye-Tracking, *Journal of experimental psychology. Human perception and performance*, 46(9), pp.871–889.
- Zeman, A., Dewar, M. and Della Sala, S. (2015) Lives without imagery – Congenital aphantasia, *Cortex*, 73, pp.378–380.
- Zeman, A. (2021) Blind Mind's Eye: People with aphantasia cannot visualize imagery, a trait that highlights the complexities of imagination and mental representation, *American scientist*, 109(2), p.110.

Appendix 8: DCC 2022 poster presentation



Appendix 9: Categorisation of papers reviewed for Chapter 2 as per the FMIR

Dimensions – ●

Processes – ♥

Modalities - ♦

- Adharamadinka and Junaidy 2022 ●
- Allen 2010 ●♦♥
- Andrade *et al.* 2014 ●♦
- Athavankar 1997 ♦♥
- Bainbridge *et al.* 2021 ●
- Bensafi *et al.* 2012 ♦
- Bilda and Gero 2008 ♦♥
- Bilda, Gero and Purcell 2006 ♦♥
- Callow and Hardy 2004 ♦
- Casakin and Kreitler 2011 ♥
- Christensen and Schunn 2009 ♥
- Chun and Hupé 2016 ●♥
- Cindioglu, Gursel and Surer 2021 ●
- Croijmans and Wang 2022 ●♦♥
- Croijmans *et al.* 2019 ●♦
- Cui *et al.* 2007 ●♦
- Dahl, Chattopadhyay and Gorn 1999 ●♦♥
- Dahl, Chattopadhyay and Gorn 2001 ♦♥
- D'Argembeau and van der Linden 2006 ♦♥
- Dijkstra *et al.* 2017 ●♦♥
- Dijkstra *et al.* 2019 ●♦♥
- Dijkstra, Bosch and van Gerven 2019 ●♦♥
- Finke and Slayton 1988 ♥
- Floridou, Peerdeman and Schaefer 2021 ●♦♥
- Gaber and Eltemamy 2021 ●
- Gallace 2012 ●♦
- Gallagher 2019 ●

- Gero and Kannengiesser 2004 ●
- Gero and McNeill 1998 ●
- Gero and Milovanovic 2020 ●♥
- Goldschmidt 1991 ♥
- Goldschmidt 1994 ♦♥
- Goldschmidt 2007 ♦♦♥
- Goldschmidt 2014 ●
- Hart and Hay 2022 ♦♦
- Hawley 2022 ♦♦
- Hay *et al.* 2017 ●
- Herd and Mehta 2019 ♦♥
- Heuer, Fischman and Reisberg 1986 ●♥
- Heylighen and Gero 2011 ♦♥
- Holmes and Mathews 2010 ♦
- Holtrop *et al.* 2021 ●
- Isaac, Marks and Russell 1986 ●
- Ji *et al.* 2022 ♦♥
- Kan and Gero 2008 ●
- Kavakli and Gero 2001 ♦♦♥
- Keogh and Pearson 2018 ♦♦
- Kokotovich and Purcell 2000 ♥
- Kosslyn, Behrmann and Jeannerod 1995 ♥
- Kozhevnikov *et al.* 2013 ●♥
- Laeng and Suluvedt 2014 ♦♦♥
- Lawrie, Hay and Wodehouse 2022 ●
- Leblebici-Başar and Altarriba 2013 ♦♦
- LeBoutillier and Marks 2003 ●♥
- Maciel *et al.* 2021 ♦♥
- Marks 1973 ●♥
- Martindale 1990 ♥
- Milton *et al.* 2021 ♦♦
- Nanay 2018 ♦
- Palmiero *et al.* 2009 ♦

- Palmiero *et al.* 2015 ●♦♥
- Palmiero *et al.* 2016 ●♦
- Pearson 2007 ♥
- Pearson 2019 ●♦♥
- Pearson, Rademaker and Tong 2011 ♦♥
- Rademaker and Pearson 2012 ●♦♥
- Rhodes 1981 ●♥
- Richardson 1991 ●♥
- Roberts *et al.* 2008 ●♦
- Shealy *et al.* 2023 ●♥
- Sheehan 1967 ●♦
- Subirats *et al.* 2018 ●♦
- Suwa, Purcell and Gero 1998 ●♥
- Taruffi *et al.* 2019 ♦♥
- Tedjosaputro and Shih 2019 ●♥
- Tedjosaputro *et al.* 2014 ♥
- Tedjosaputro *et al.* 2017 ●♥
- Tedjosaputro *et al.* 2018 ●♥
- Van der Schaaf *et al.* 2019 ●♥
- Voyer *et al.* 2020 ●
- Zeman 2021 ●♦

Appendix 10: Chapter 7 questionnaire

Design Emotion & Experience mental imagery study

Mental imagery is the experience of perceiving an image in one's own mind, for example, if I asked you to picture a horse in a field of yellow flowers you would (potentially) have an image of it within your mind, or if I asked you to imagine the smell of the rose, you may be able to smell it as if there is a rose present. This research project is attempting to specify exactly when, where and how mental imagery is experienced by designers within a design project.

The aim of this questionnaire is to provide an approximate measure for the vividness of your mental imagery for varying senses and modalities.

The survey will take approximately 10 minutes to complete. Please complete all parts of this questionnaire. For the first 7 sections, please complete by assigning a 0-10 rating using the following scale:

- 0 - no image at all
- 1
- 2
- 3
- 4
- 5 - moderately clear and vivid image
- 6
- 7
- 8
- 9
- 10 - perfectly clear and vivid as real life

You are invited to take part in this study as part of a wider research project which is being conducted by Rebecca Macfie for her PhD research at the University of Strathclyde in Glasgow, Scotland. Completion of this survey is voluntary - to opt-out please email Rebecca via the contact details below. By completing this survey, you are giving explicit consent for taking part in this study and for the responses provided to be used for and within research reports for this project, as well as for your DM300 final outcome to be accessed for comparison purposes. All personal information will be kept entirely confidential, deleted following successful completion of this project, and any reference to your individual responses will be anonymised. Please read the the information sheet attached to the email, and the deadline for completion of this questionnaire is 12pm Friday 22nd November 2024.

If you have any questions regarding any of the information here, please contact Rebecca via email at rebecca.macfie@strath.ac.uk or by phone at 0141 552 2600.

Imagine the appearance of:

1. A friend you know well *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image Vivid as real life

Imagine the sound of:

6. An ambulance siren *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life
7. Hands clapping in applause *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life
8. The mewling of a cat *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life
9. The sound of a car horn *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life
10. The sound of children playing *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life

2. A cat climbing a tree *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life
3. A sunset *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life
4. The front door of your house *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life
5. A bonfire *
- | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|----|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|----|
- No image
- Vivid as real life

Imagine the bodily sensation of:

16. Relaxing in a warm bath *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

17. Having a sore throat *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

18. Threading a needle *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

19. Jumping into a swimming pool *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

20. Walking briskly in the cold *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

Imagine touching:

11. Warm sand *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

12. A soft towel *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

13. The point of a pin *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

14. Icy water *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

15. Fur *

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

No image

Vivid as real life

Other cognition questions

26. Do you, as far as you're aware, experience synesthesia (the experience of multiple senses at once, i.e. tasting words or seeing numbers as colours)? *

- ☐ Yes
☐ No
☐ Unsure

27. How would you rate your memory on a scale of 1-10, with 10 being a photographic memory? *

0	1	2	3	4	5	6	7	8	9	10
No memory					Photographic memory					

28. How would you rate your imagination on a scale of 1-10, with 10 being a extremely imaginative? *

0	1	2	3	4	5	6	7	8	9	10
No imagination					Extremely imaginative					

29. If you experience mental imagery, would you describe it as voluntary, involuntary, both, or neither? *

- ☐ Voluntary
☐ Involuntary
☐ Both
☐ Neither (go to question 30)

Imagine feeling:

21. Excited *

0	1	2	3	4	5	6	7	8	9	10
No image					Vivid as real life					

22. Relieved *

0	1	2	3	4	5	6	7	8	9	10
No image					Vivid as real life					

23. Furious *

0	1	2	3	4	5	6	7	8	9	10
No image					Vivid as real life					

24. In love *

0	1	2	3	4	5	6	7	8	9	10
No image					Vivid as real life					

25. Scared *

0	1	2	3	4	5	6	7	8	9	10
No image					Vivid as real life					

34. Is there anything else you would like to add to explain your mental imagery experience?

30. Please provide further information if you selected "neither" to question 29.

31. If you experience visual mental imagery, can you visualise in 2D, 3D, both, neither, or other? *

- ☐ 2D
☐ 3D
☐ Both
☐ Neither (go to question 32)

32. Please provide further information if you selected "neither" or "other" to question 31

33. If you experience visual mental imagery, how easy do you find it to translate the images in your head to paper? *

- ☐ Extremely easy
☐ Somewhat easy
☐ Neutral
☐ Somewhat not easy
☐ Extremely not easy

Additional information

38. What is your full name? *

39. What is your student email address? *

40. Please provide your student registration number *

41. Please select your undergraduate course from the list below: *

- ☐ PDE
☐ PDI
☐ SDE
☐ Other (please specify)

42. Are you happy to be contacted for future research in relation to this project via email? *

- ☐ Yes
☐ No

Design Emotion & Experience project

35. What emotion have you chosen for your project? *

36. How have you found the Design Emotion & Experience project so far? *



37. Please elaborate on your rating for question 36. *

43. Would you like to be notified of any research papers published with the results of this study? *

☐ Yes

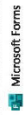
☐ No

44. Do you give permission for images of your final course project to be used in papers produced for this study? *

☐ Yes

☐ No

This content is neither created nor endorsed by Microsoft. The data you submit will be sent to the form owner.



Appendix 11: Chapter 7 DM300 PSIQ responses

PSIQ	Appearance					Sound				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
P1	7.00	9.00	8.00	10.00	7.00	6.00	9.00	10.00	7.00	6.00
P2	10.00	5.00	8.00	7.00	4.00	9.00	8.00	9.00	10.00	3.00
P3	10.00	6.00	10.00	8.00	9.00	4.00	6.00	4.00	5.00	5.00
P4	6.00	4.00	7.00	9.00	6.00	8.00	10.00	8.00	10.00	6.00
P5	10.00	7.00	9.00	10.00	10.00	8.00	9.00	6.00	7.00	4.00
P6	10.00	10.00	10.00	10.00	10.00	3.00	7.00	8.00	4.00	3.00
P7	7.00	6.00	4.00	8.00	6.00	3.00	7.00	3.00	3.00	2.00
P8	10.00	8.00	8.00	9.00	8.00	10.00	10.00	7.00	9.00	4.00
P9	9.00	6.00	8.00	7.00	6.00	8.00	9.00	6.00	9.00	7.00
P10	10.00	9.00	9.00	8.00	9.00	7.00	10.00	10.00	10.00	8.00
P11	10.00	10.00	10.00	10.00	10.00	10.00	10.00	6.00	10.00	9.00
P12	8.00	9.00	9.00	9.00	9.00	8.00	8.00	9.00	9.00	9.00
P13	7.00	5.00	5.00	8.00	6.00	10.00	9.00	9.00	10.00	10.00
P14	7.00	6.00	9.00	9.00	8.00	5.00	9.00	10.00	10.00	8.00
P15	8.00	6.00	7.00	7.00	7.00	5.00	6.00	7.00	7.00	5.00
P16	9.00	6.00	7.00	8.00	5.00	3.00	5.00	2.00	3.00	6.00
P17	4.00	4.00	4.00	4.00	4.00	6.00	7.00	7.00	6.00	6.00
P18	10.00	10.00	10.00	10.00	10.00	8.00	8.00	7.00	9.00	8.00
P19	8.00	9.00	9.00	10.00	10.00	9.00	9.00	9.00	9.00	9.00
P20	5.00	5.00	5.00	5.00	5.00	3.00	5.00	6.00	4.00	2.00
P21	8.00	7.00	6.00	8.00	8.00	6.00	7.00	5.00	6.00	6.00
P22	8.00	6.00	7.00	10.00	4.00	5.00	10.00	7.00	6.00	5.00
P23	10.00	10.00	10.00	10.00	10.00	7.00	9.00	10.00	9.00	10.00
P24	9.00	9.00	6.00	9.00	7.00	6.00	8.00	8.00	5.00	6.00
P25	10.00	7.00	9.00	9.00	6.00	6.00	9.00	10.00	10.00	7.00
P26	7.00	6.00	8.00	8.00	7.00	5.00	6.00	4.00	6.00	4.00
P27	6.00	10.00	10.00	8.00	9.00	9.00	8.00	9.00	8.00	6.00
P28	5.00	4.00	8.00	8.00	8.00	5.00	8.00	5.00	7.00	4.00
P29	10.00	10.00	10.00	10.00	10.00	9.00	8.00	7.00	8.00	5.00
P30	10.00	10.00	10.00	10.00	10.00	8.00	10.00	10.00	10.00	8.00
P31	6.00	9.00	9.00	7.00	6.00	4.00	5.00	2.00	3.00	3.00

PS/Q	Touching					Bodily sensations					Feeling				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
P1	6.00	4.00	7.00	9.00	10.00	5.00	10.00	6.00	8.00	10.00	9.00	8.00	6.00	7.00	6.00
P2	6.00	4.00	4.00	8.00	6.00	9.00	6.00	2.00	5.00	5.00	7.00	8.00	10.00	10.00	3.00
P3	8.00	6.00	4.00	6.00	6.00	4.00	4.00	3.00	7.00	5.00	5.00	4.00	7.00	9.00	2.00
P4	8.00	7.00	6.00	5.00	7.00	4.00	6.00	6.00	8.00	7.00	2.00	3.00	1.00	3.00	2.00
P5	7.00	8.00	6.00	9.00	4.00	7.00	6.00	2.00	9.00	9.00	8.00	6.00	4.00	5.00	7.00
P6	2.00	2.00	3.00	2.00	4.00	4.00	7.00	0.00	1.00	1.00	4.00	7.00	6.00	10.00	4.00
P7	8.00	9.00	10.00	9.00	10.00	9.00	7.00	9.00	7.00	8.00	8.00	3.00	7.00	8.00	9.00
P8	7.00	6.00	9.00	5.00	6.00	6.00	9.00	9.00	8.00	8.00	10.00	10.00	7.00	9.00	10.00
P9	9.00	9.00	9.00	8.00	9.00	8.00	8.00	8.00	9.00	9.00	9.00	9.00	9.00	7.00	9.00
P10	6.00	10.00	10.00	10.00	10.00	10.00	10.00	7.00	8.00	7.00	7.00	8.00	5.00	3.00	7.00
P11	10.00	10.00	10.00	10.00	6.00	5.00	8.00	0.00	10.00	10.00	2.00	0.00	3.00	0.00	1.00
P12	9.00	9.00	6.00	6.00	6.00	8.00	2.00	4.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
P13	8.00	7.00	8.00	8.00	8.00	9.00	8.00	9.00	7.00	9.00	9.00	9.00	7.00	0.00	4.00
P14	4.00	4.00	8.00	4.00	6.00	5.00	9.00	3.00	7.00	7.00	5.00	5.00	5.00	5.00	5.00
P15	7.00	5.00	7.00	7.00	6.00	7.00	8.00	6.00	6.00	6.00	7.00	8.00	8.00	9.00	6.00
P16	8.00	4.00	2.00	8.00	3.00	3.00	4.00	7.00	8.00	3.00	5.00	6.00	4.00	3.00	7.00
P17	3.00	3.00	4.00	4.00	3.00	7.00	6.00	7.00	7.00	7.00	8.00	8.00	3.00	8.00	4.00
P18	9.00	9.00	9.00	9.00	8.00	6.00	9.00	6.00	10.00	9.00	10.00	10.00	10.00	10.00	10.00
P19	8.00	9.00	7.00	9.00	9.00	8.00	9.00	8.00	9.00	9.00	8.00	7.00	6.00	8.00	7.00
P20	4.00	6.00	6.00	5.00	7.00	4.00	3.00	5.00	4.00	5.00	5.00	5.00	5.00	5.00	5.00
P21	6.00	7.00	7.00	7.00	6.00	7.00	6.00	5.00	6.00	7.00	7.00	7.00	5.00	6.00	6.00
P22	3.00	4.00	6.00	8.00	7.00	4.00	6.00	8.00	9.00	10.00	5.00	2.00	3.00	0.00	5.00
P23	9.00	10.00	9.00	10.00	10.00	10.00	7.00	10.00	9.00	10.00	10.00	10.00	8.00	9.00	10.00
P24	6.00	7.00	8.00	7.00	7.00	7.00	8.00	8.00	8.00	8.00	2.00	3.00	4.00	7.00	9.00
P25	7.00	4.00	8.00	3.00	9.00	4.00	9.00	4.00	5.00	8.00	3.00	7.00	3.00	6.00	5.00
P26	4.00	4.00	6.00	6.00	5.00	7.00	7.00	4.00	5.00	4.00	8.00	9.00	9.00	9.00	9.00
P27	7.00	8.00	6.00	9.00	8.00	8.00	6.00	6.00	8.00	9.00	8.00	6.00	4.00	6.00	5.00
P28	4.00	4.00	7.00	8.00	8.00	4.00	4.00	4.00	4.00	4.00	5.00	5.00	5.00	5.00	5.00
P29	8.00	10.00	6.00	6.00	8.00	10.00	7.00	3.00	7.00	9.00	6.00	9.00	10.00	2.00	5.00
P30	9.00	7.00	6.00	8.00	10.00	10.00	7.00	4.00	8.00	10.00	10.00	8.00	5.00	5.00	7.00
P31	5.00	2.00	7.00	3.00	4.00	5.00	5.00	7.00	7.00	9.00	3.00	5.00	6.00	7.00	5.00

Appendix 12: Chapter 7 DM983 PSIQ responses

PSIQ	Appearance					Sound				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
T1	10.00	7.00	8.00	10.00	8.00	5.00	6.00	8.00	8.00	5.00
T2	8.00	5.00	7.00	7.00	5.00	6.00	8.00	9.00	5.00	4.00
T3	9.00	8.00	8.00	10.00	9.00	9.00	8.00	6.00	7.00	8.00
T4	9.00	8.00	10.00	8.00	8.00	9.00	9.00	9.00	9.00	9.00
T5	10.00	8.00	10.00	10.00	2.00	2.00	7.00	2.00	4.00	0.00
T7	9.00	7.00	8.00	10.00	5.00	3.00	10.00	8.00	6.00	8.00
T8	5.00	3.00	8.00	3.00	8.00	4.00	8.00	7.00	3.00	2.00
T9	6.00	4.00	8.00	4.00	7.00	9.00	10.00	9.00	10.00	10.00
T10	9.00	8.00	9.00	10.00	6.00	6.00	6.00	4.00	9.00	9.00
T11	3.00	4.00	4.00	5.00	4.00	2.00	2.00	4.00	3.00	1.00
T12	10.00	10.00	9.00	7.00	10.00	10.00	10.00	10.00	6.00	10.00

PSIQ	Touching					Bodily sensations					Feeling				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
T1	7.00	8.00	9.00	9.00	6.00	8.00	8.00	9.00	6.00	7.00	8.00	9.00	5.00	8.00	6.00
T2	5.00	7.00	8.00	8.00	6.00	6.00	8.00	5.00	6.00	8.00	5.00	4.00	7.00	9.00	8.00
T3	7.00	8.00	9.00	8.00	7.00	7.00	8.00	8.00	8.00	8.00	9.00	9.00	8.00	8.00	9.00
T4	7.00	7.00	8.00	7.00	8.00	8.00	8.00	6.00	7.00	8.00	7.00	7.00	7.00	8.00	10.00
T5	7.00	4.00	0.00	3.00	3.00	2.00	5.00	5.00	7.00	10.00	8.00	3.00	2.00	7.00	4.00
T7	8.00	8.00	10.00	6.00	5.00	7.00	9.00	3.00	8.00	7.00	7.00	8.00	4.00	6.00	6.00
T8	8.00	8.00	8.00	8.00	8.00	8.00	7.00	9.00	6.00	6.00	8.00	8.00	5.00	3.00	5.00
T9	9.00	10.00	10.00	10.00	9.00	10.00	10.00	9.00	6.00	9.00	10.00	10.00	7.00	10.00	9.00
T10	8.00	9.00	6.00	8.00	6.00	9.00	5.00	4.00	8.00	8.00	9.00	9.00	8.00	9.00	6.00
T11	4.00	4.00	5.00	5.00	5.00	3.00	4.00	3.00	4.00	4.00	7.00	7.00	8.00	8.00	8.00
T12	10.00	10.00	9.00	8.00	7.00	7.00	10.00	10.00	6.00	6.00	4.00	4.00	4.00	4.00	4.00

Appendix 13: VVIQ (Marks 1983)

Vividness of Visual Imagery Questionnaire

Mental imagery is the experience of perceiving an image in one's own mind, for example, if I asked you to picture a horse in a field of yellow flowers you would (potentially) have an image of it within your mind, or if I asked you to imagine the smell of the rose, you may be able to smell it as if there is a rose present. This research project is attempting to specify exactly when, where and how mental imagery is experienced by designers within a design project.

The aim of this questionnaire is to provide an approximate measure for the vividness of your visual mental imagery. Complete sections 1-4 with your eyes open, then sections 5-8 with your eyes closed. You are asked to rate the vividness of each image using the following scale:

- 1 - No image at all, I only "know" I am thinking of the object
2 - Dim and vague image
3 - Moderately realistic and vivid
4 - Realistic and reasonably vivid
5 - Perfectly realistic, as vivid as real seeing

You are invited to take part in this study as part of a wider research project which is being conducted by Rebecca Macfie for her PhD research at the University of Strathclyde in Glasgow, Scotland. By completing this survey, you are giving explicit consent for taking part in this study and for the responses provided to be used for and within research reports for this project. All personal information will be kept entirely confidential, deleted following successful completion of this project, and any reference to your individual responses will be anonymised. Please read the the information sheet attached to the email, and please complete this questionnaire before your study time.

If you have any questions regarding any of the information here, please contact Rebecca Macfie at rebecca.mchugh.2020@uni.strath.ac.uk.

The University of Strathclyde is registered with the Information Commissioner's Office who

Relative or friend

Please have your eyes open for this section. For items 1 to 4, think of some relative or friend whom you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind's eye.

1. Imagine the exact contour of face, head, shoulders, and body. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

Natural scene: Rising sun

Please have your eyes open for this section. For items 5 to 8, visualise a rising sun, and consider carefully the picture that comes before your mind's eye.

5. Imagine the sun is rising above the horizon into a hazy sky. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

6. Imagine the sky clears and surrounds the sun with blueness. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

7. Imagine clouds. A storm blows up, with flashes of lightning. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

2. Imagine characteristic poses of head, attitudes of body, etc. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

3. Imagine the precise carriage, length of step, etc. in walking. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

4. Imagine the different colours worn in some familiar clothes. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

- Shop**
- Please have your eyes open for this section. For items 9 to 12, think of the front of a shop which you often go to, and consider carefully the picture that comes before your mind's eye.
8. Imagine a rainbow appears. *
- ☐ 1 - no image at all
 - ☐ 2 - vague and dim
 - ☐ 3 - moderately clear and vivid
 - ☐ 4 - clear and reasonably vivid
 - ☐ 5 - perfectly clear and vivid as real life
9. Imagine the overall appearance of the shop from the opposite side of the road. *
- ☐ 1 - no image at all
 - ☐ 2 - vague and dim
 - ☐ 3 - moderately clear and vivid
 - ☐ 4 - clear and reasonably vivid
 - ☐ 5 - perfectly clear and vivid as real life
10. Imagine a window display including colours, shape, and details of individual items for sale. *
- ☐ 1 - no image at all
 - ☐ 2 - vague and dim
 - ☐ 3 - moderately clear and vivid
 - ☐ 4 - clear and reasonably vivid
 - ☐ 5 - perfectly clear and vivid as real life
11. Imagine you are near the entrance. The colour, shape, and details of the door. *
- ☐ 1 - no image at all
 - ☐ 2 - vague and dim
 - ☐ 3 - moderately clear and vivid
 - ☐ 4 - clear and reasonably vivid
 - ☐ 5 - perfectly clear and vivid as real life

Natural scene: Lake

Please have your eyes open for this section. For items 13 to 16, think of a country scene which involves trees, mountains, and a lake, and consider carefully the picture that comes before your mind's eye.

13. Imagine the contours of the landscape. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

14. Imagine the colour and shape of the trees. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

15. Imagine the colour and shape of the lake. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

12. Imagine you enter the shop and go to the counter. The counter assistant serves you. Money changes hands. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

16. Imagine a strong wind blows on the tree and on the lake causing waves. *

- ☐ 1 - no image at all
☐ 2 - vague and dim
☐ 3 - moderately clear and vivid
☐ 4 - clear and reasonably vivid
☐ 5 - perfectly clear and vivid as real life

Relative or friend

Please have your eyes closed for this section. For items 17 to 20, think of some relative or friend whom you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind's eye.

17. Imagine the exact contour of face, head, shoulders, and body. *

- ☐ 1 - no image at all
☐ 2 - vague and dim
☐ 3 - moderately clear and vivid
☐ 4 - clear and reasonably vivid
☐ 5 - perfectly clear and vivid as real life

18. Imagine characteristic poses of head, attitudes of body, etc. *

- ☐ 1 - no image at all
☐ 2 - vague and dim
☐ 3 - moderately clear and vivid
☐ 4 - clear and reasonably vivid
☐ 5 - perfectly clear and vivid as real life

19. Imagine the precise carriage, length of step, etc. in walking. *

- ☐ 1 - no image at all
☐ 2 - vague and dim
☐ 3 - moderately clear and vivid
☐ 4 - clear and reasonably vivid
☐ 5 - perfectly clear and vivid as real life

20. Imagine the different colours worn in some familiar clothes. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

Natural scene: Rising sun

Please have your eyes closed for this section. For items 21 to 24, visualise a rising sun, and consider carefully the picture that comes before your mind's eye.

21. Imagine the sun is rising above the horizon into a hazy sky. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

22. Imagine the sky clears and surrounds the sun with blueness. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

23. Imagine clouds. A storm blows up, with flashes of lightning. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

- Shop**
- Please have your eyes closed for this section. For items 25 to 28, think of the front of a shop which you often go to, and consider carefully the picture that comes before your mind's eye.
24. Imagine a rainbow appears. *
- ☐ 1 - no image at all
 - ☐ 2 - vague and dim
 - ☐ 3 - moderately clear and vivid
 - ☐ 4 - clear and reasonably vivid
 - ☐ 5 - perfectly clear and vivid as real life
25. Imagine the overall appearance of the shop from the opposite side of the road. *
- ☐ 1 - no image at all
 - ☐ 2 - vague and dim
 - ☐ 3 - moderately clear and vivid
 - ☐ 4 - clear and reasonably vivid
 - ☐ 5 - perfectly clear and vivid as real life
26. Imagine a window display including colours, shape, and details of individual items for sale. *
- ☐ 1 - no image at all
 - ☐ 2 - vague and dim
 - ☐ 3 - moderately clear and vivid
 - ☐ 4 - clear and reasonably vivid
 - ☐ 5 - perfectly clear and vivid as real life
27. Imagine you are near the entrance. The colour, shape, and details of the door. *
- ☐ 1 - no image at all
 - ☐ 2 - vague and dim
 - ☐ 3 - moderately clear and vivid
 - ☐ 4 - clear and reasonably vivid
 - ☐ 5 - perfectly clear and vivid as real life

Natural scene: Lake

Please have your eyes closed for this section. For items 29 to 32, think of a country scene which involves trees, mountains, and a lake, and consider carefully the picture that comes before your mind's eye.

29. Imagine the contours of the landscape. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

30. Imagine the colour and shape of the trees. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

31. Imagine the colour and shape of the lake. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

28. Imagine you enter the shop and go to the counter. The counter assistant serves you. Money changes hands. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

32. Imagine a strong wind blows on the tree and on the lake causing waves. *

- ☐ 1 - no image at all
- ☐ 2 - vague and dim
- ☐ 3 - moderately clear and vivid
- ☐ 4 - clear and reasonably vivid
- ☐ 5 - perfectly clear and vivid as real life

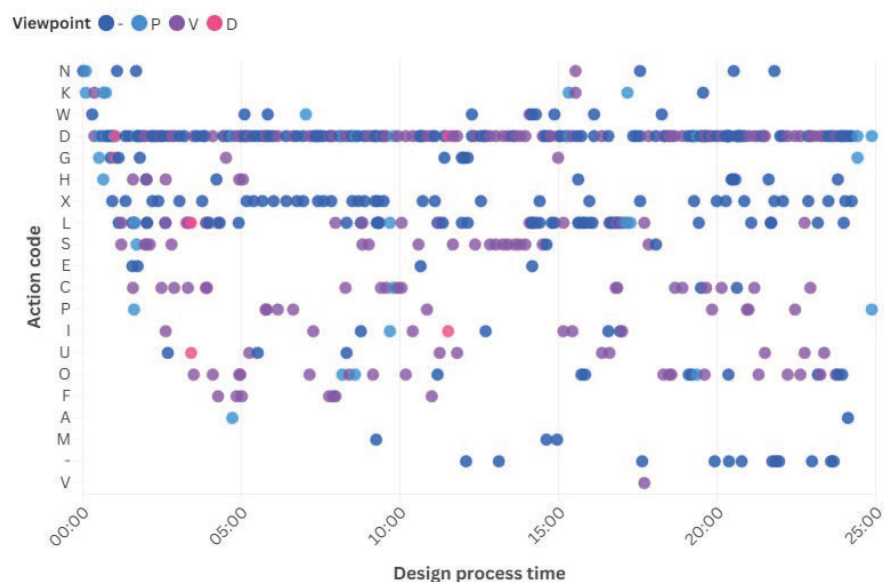
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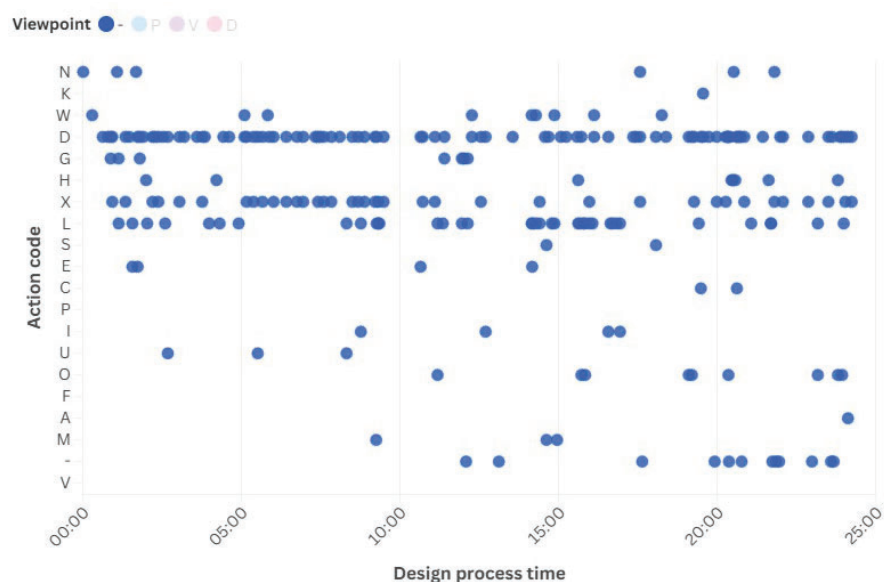
Appendix 14: Pilot session design briefs for Chapter 8

1. Drying clothes in a small apartment
2. Storing personal items in a small space
3. Gardening without a garden
4. Working from home in a shared space
5. Sharing meals in a small apartment

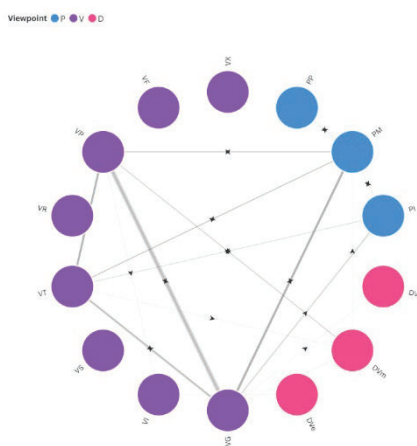
Appendix 15: P-1 full maps and networks for Chapters 8 and 9



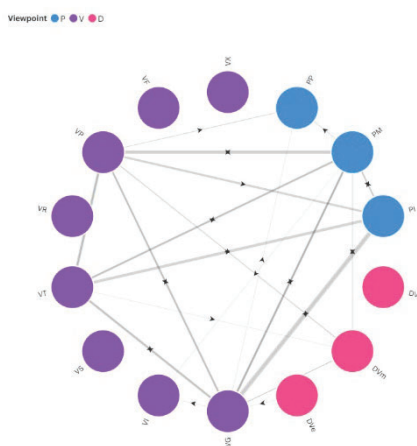
1: Overall design process map



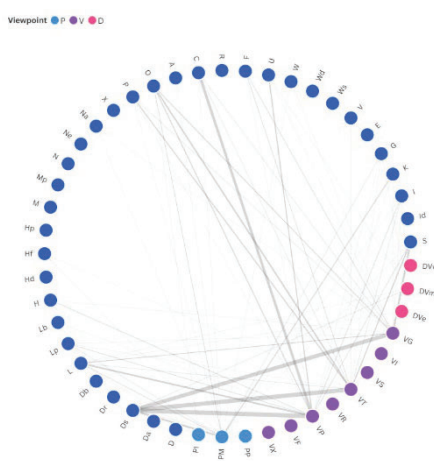
2: Action without imagery map



3: Overall back links network graph

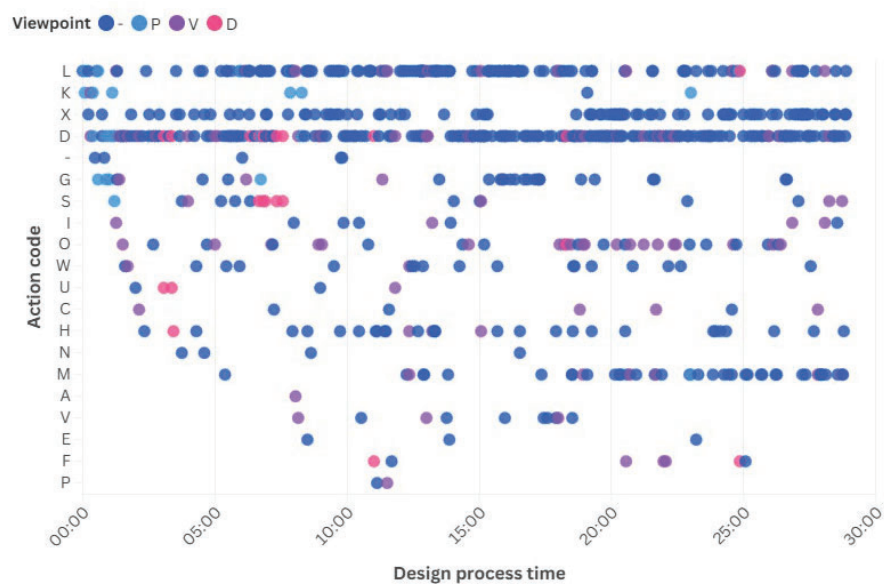


4: Overall other links network graph

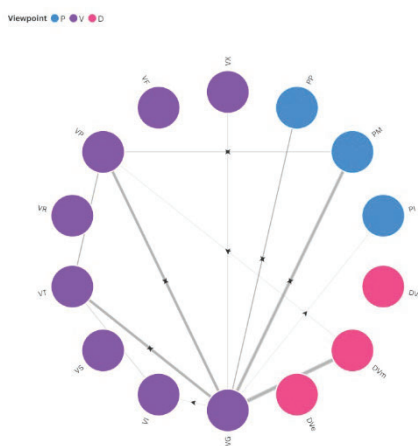


5: Overall imagery-action links network graph

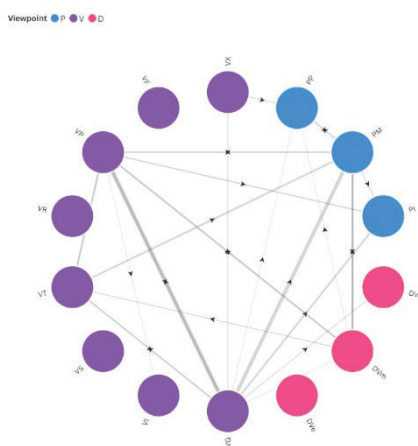
Appendix 16: P-2 full maps and networks for Chapters 8 and 9



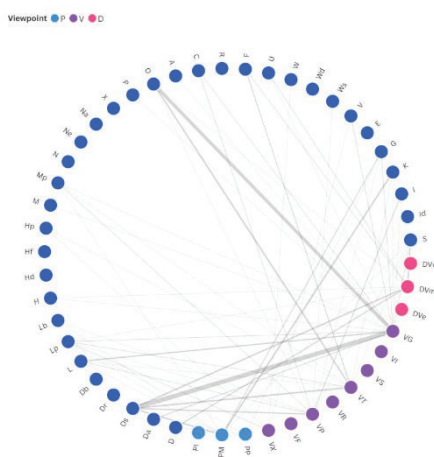
1: Overall design process map



2: Overall back links network graph



3: Overall other links network graph



4: Overall imagery-action links network graph

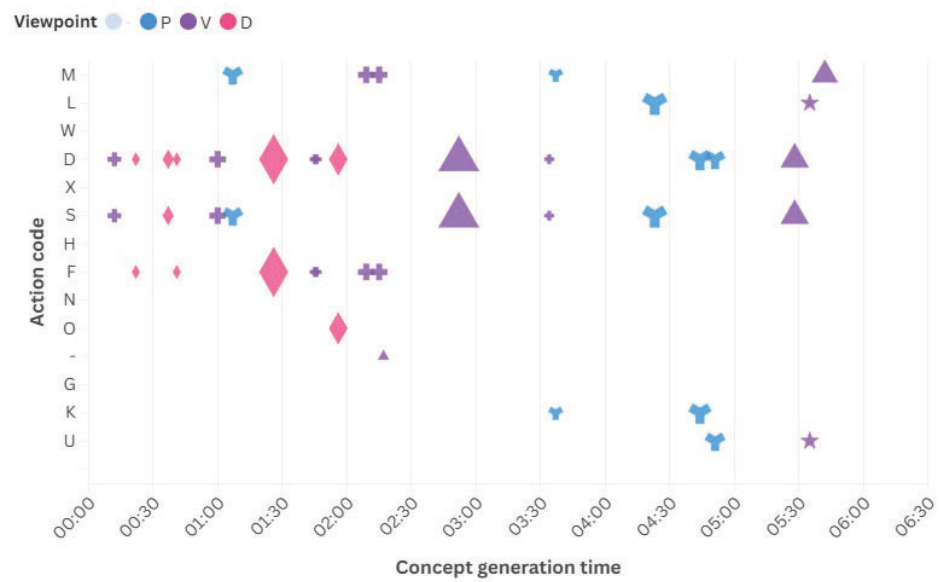
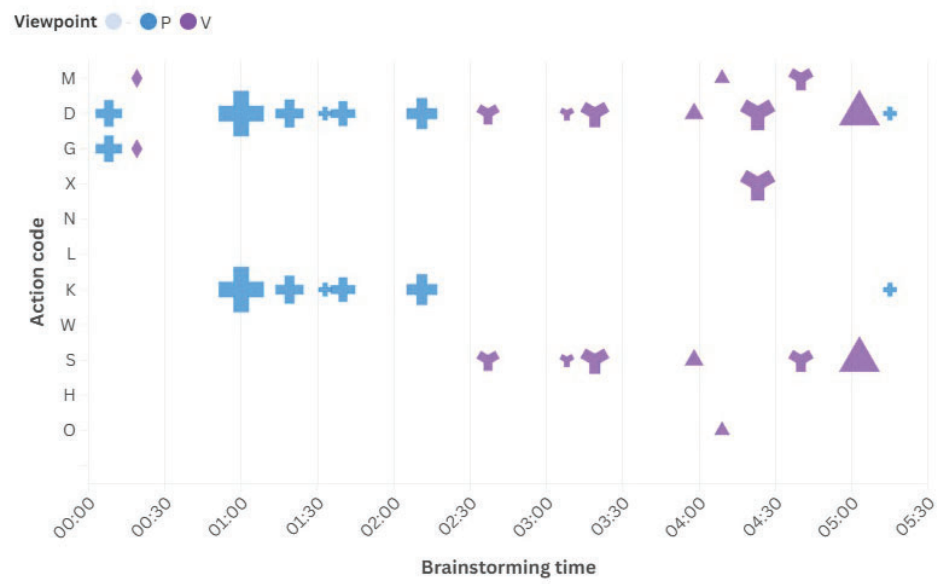
Appendix 17: P-3 full maps and networks for Chapters 8 and 9

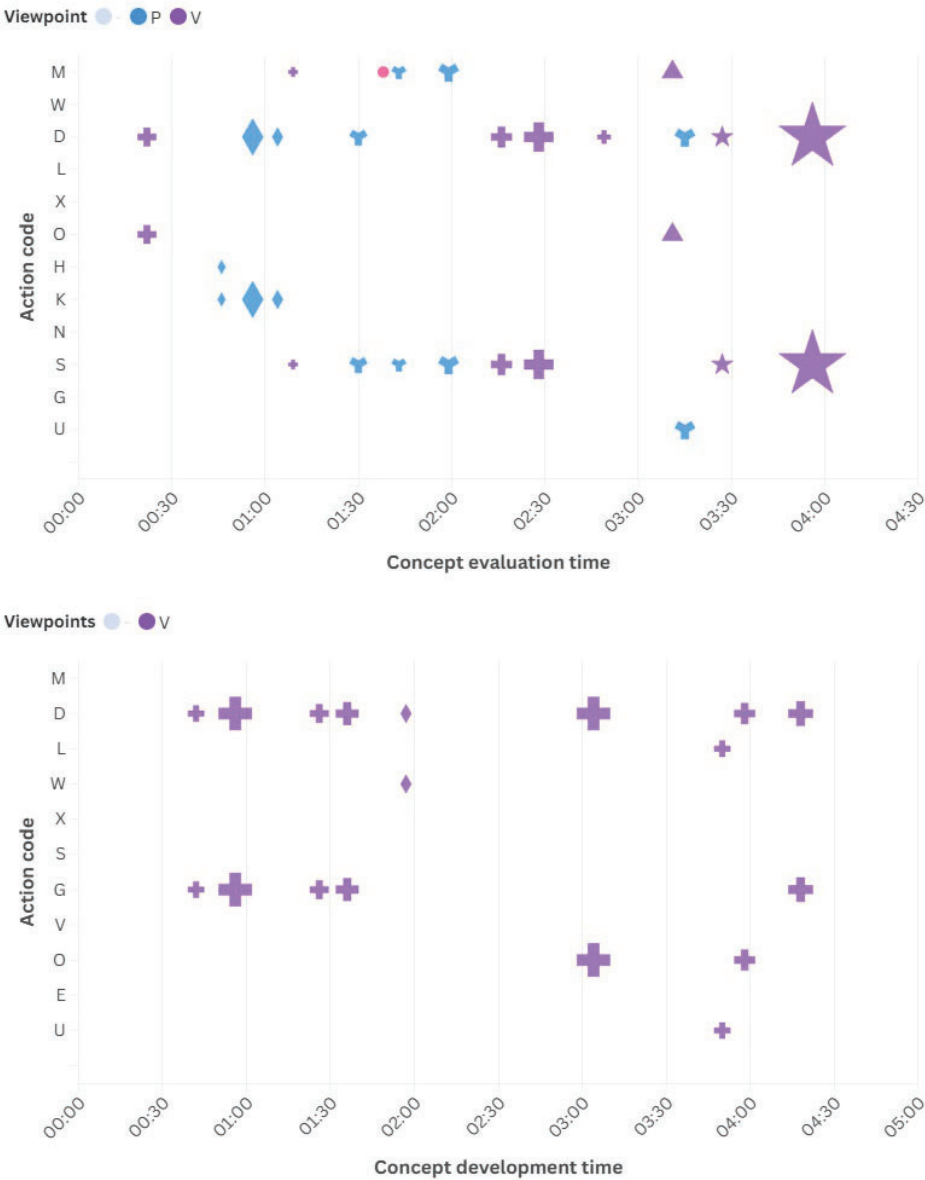


1: Overall design process map



2: Action without imagery map

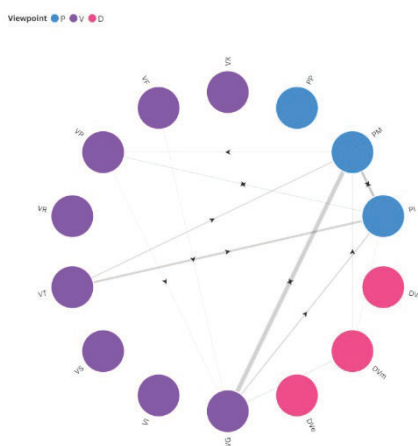




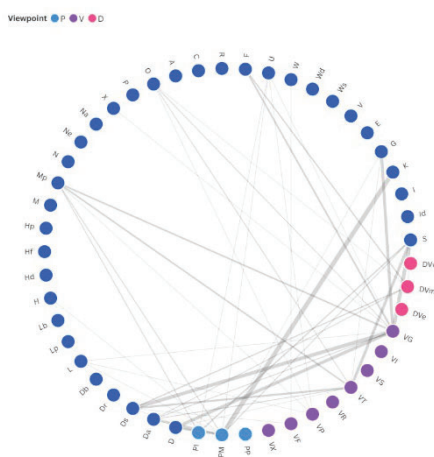
3: Imagery process maps by design stage



4: Overall back links network graph

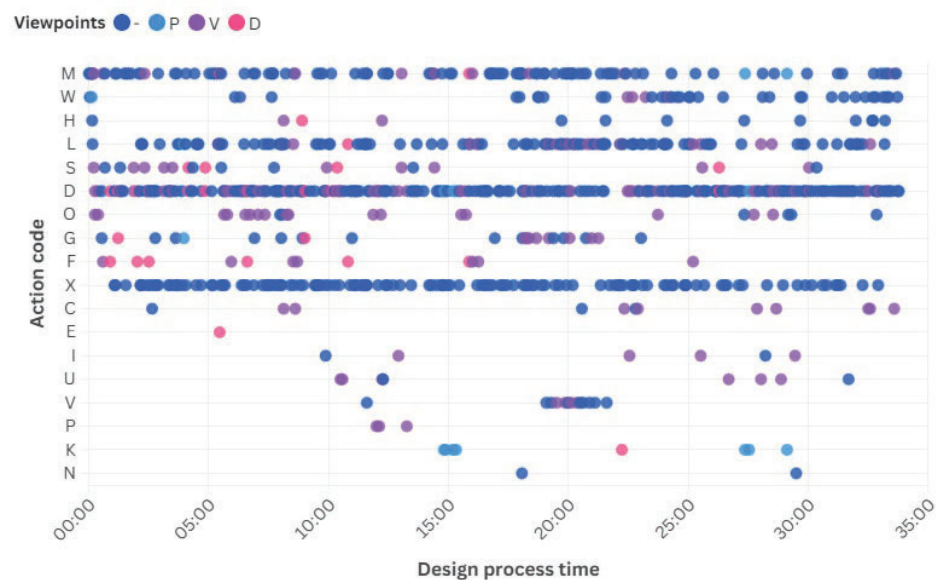


5: Overall other links network graph

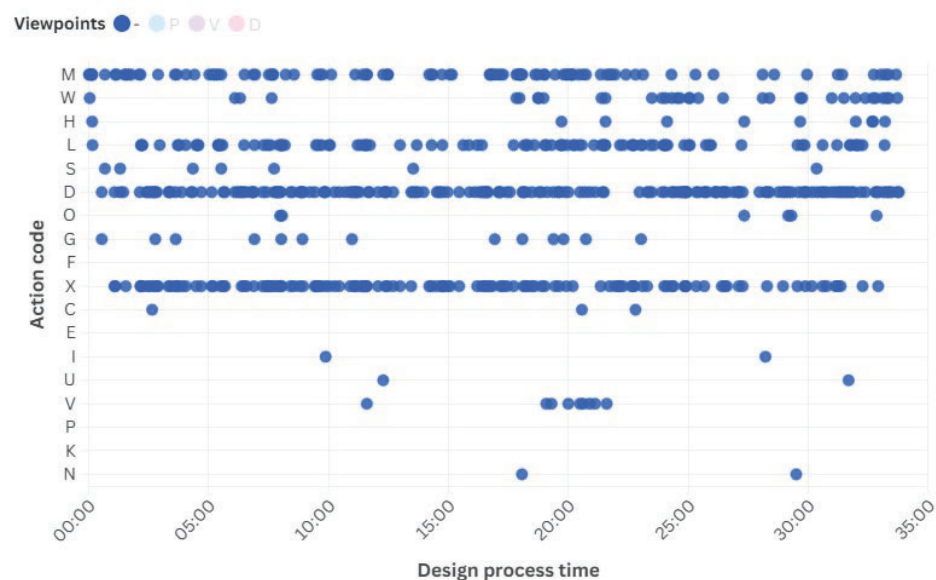


6: Overall imagery-action links network graph

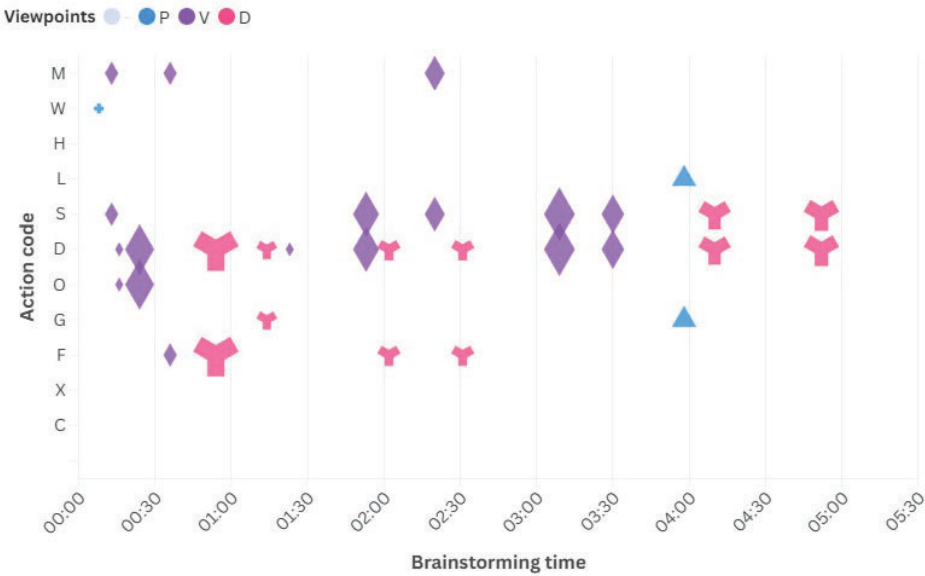
Appendix 18: P-4 full maps and networks for Chapters 8 and 9

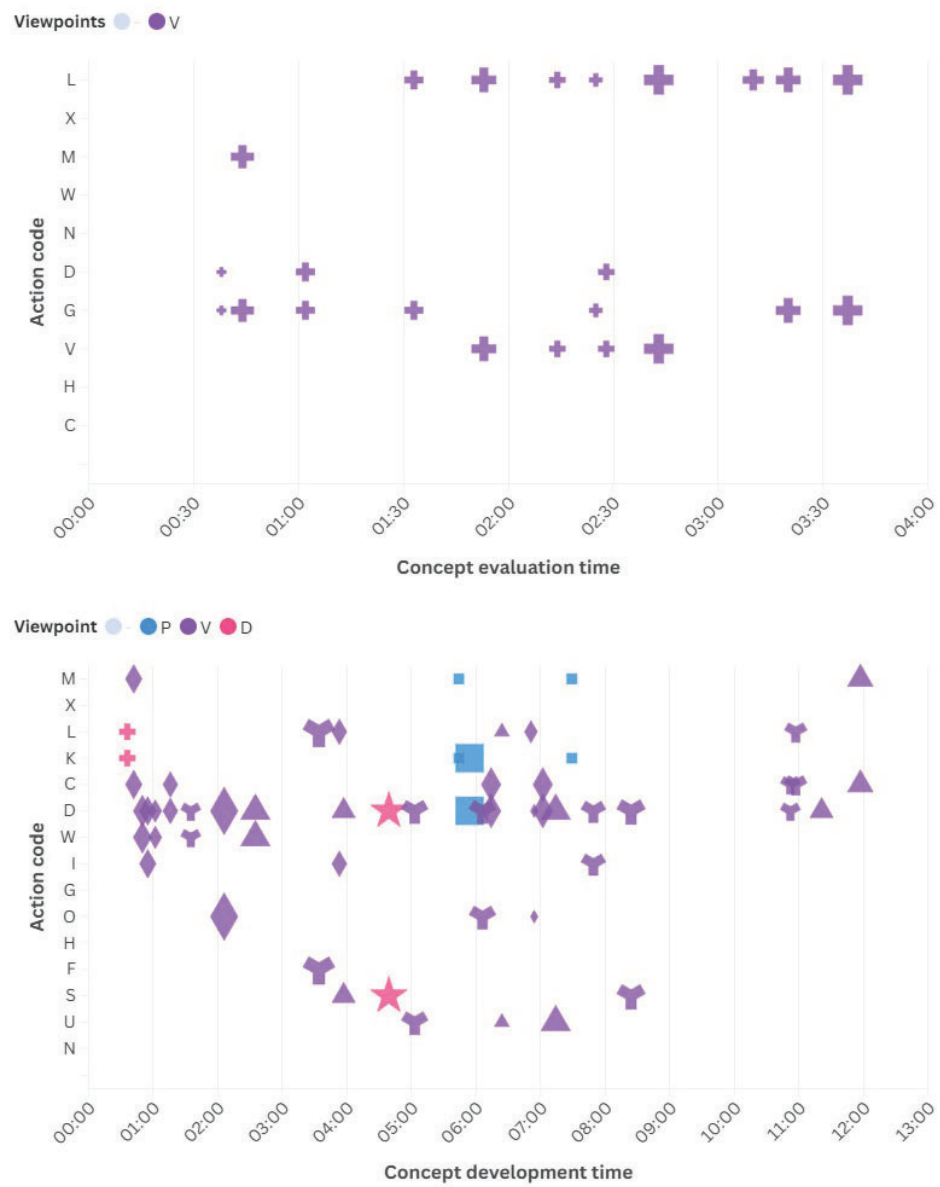


1: Overall design process map

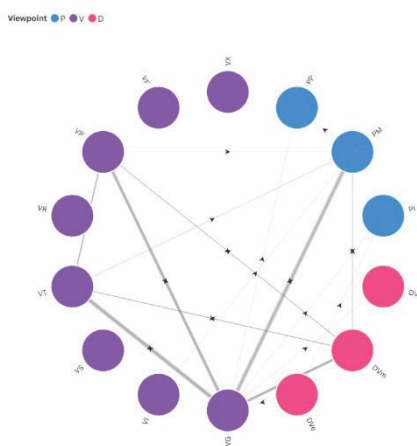


2: Action without imagery map

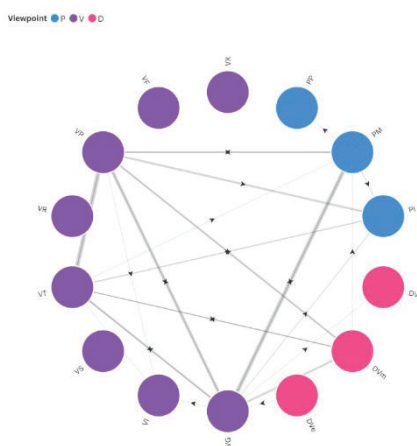




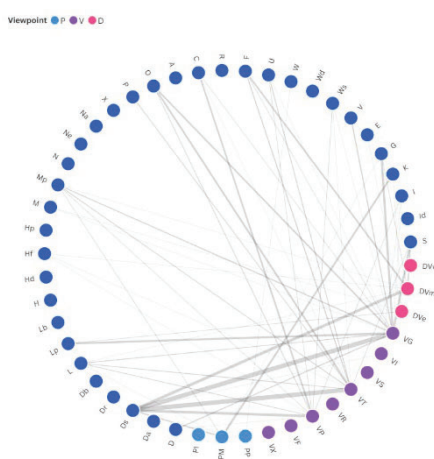
3: Imagery process maps by design stage



4: Overall back links network graph

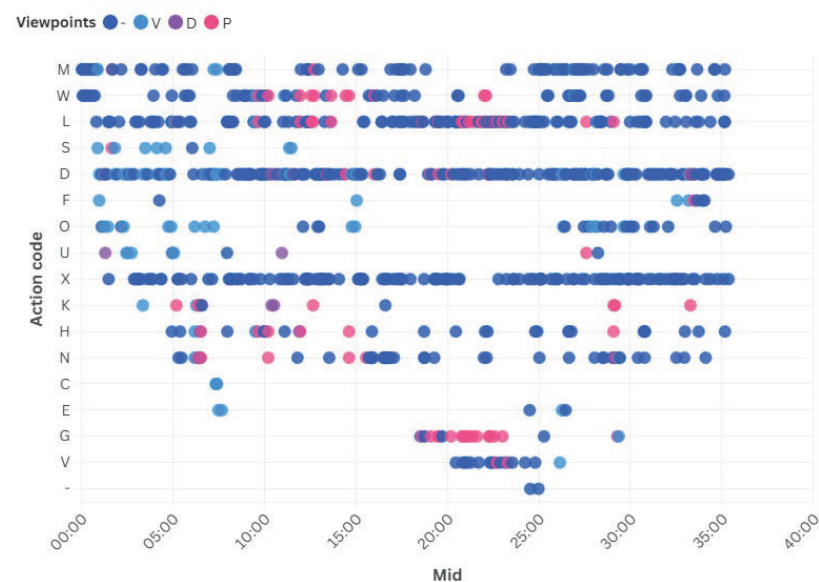


5: Overall other links network graph

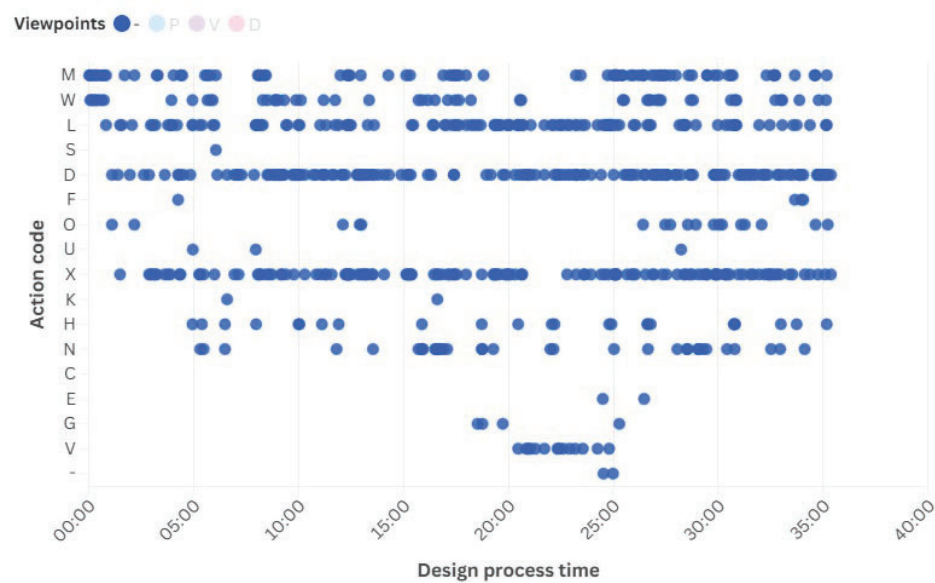


6: Overall imagery-action links network graph

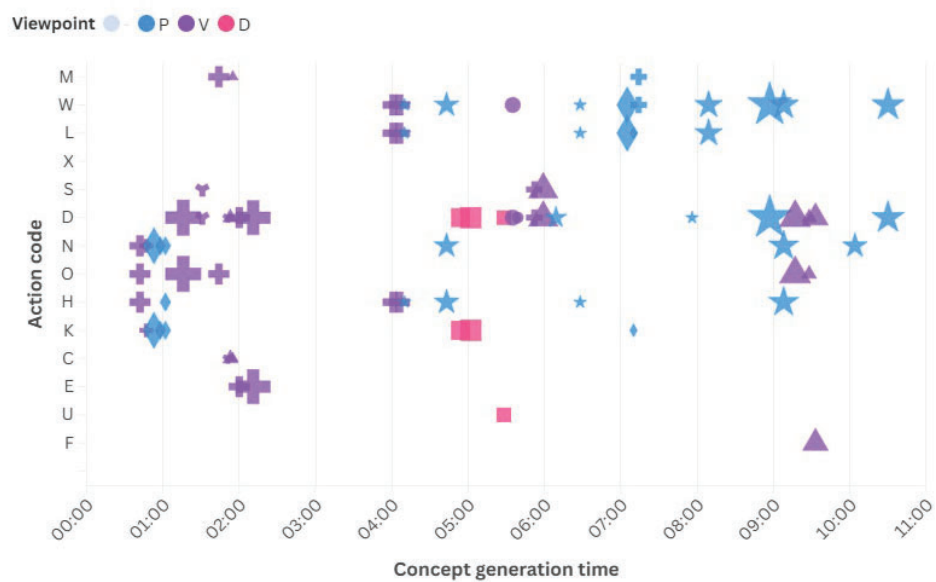
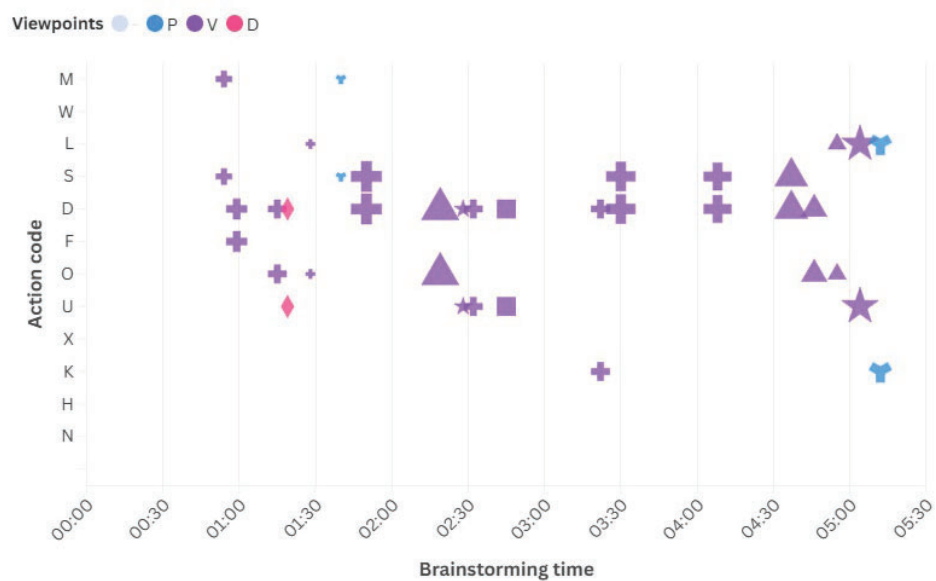
Appendix 19: P-5 full maps and networks for Chapters 8 and 9

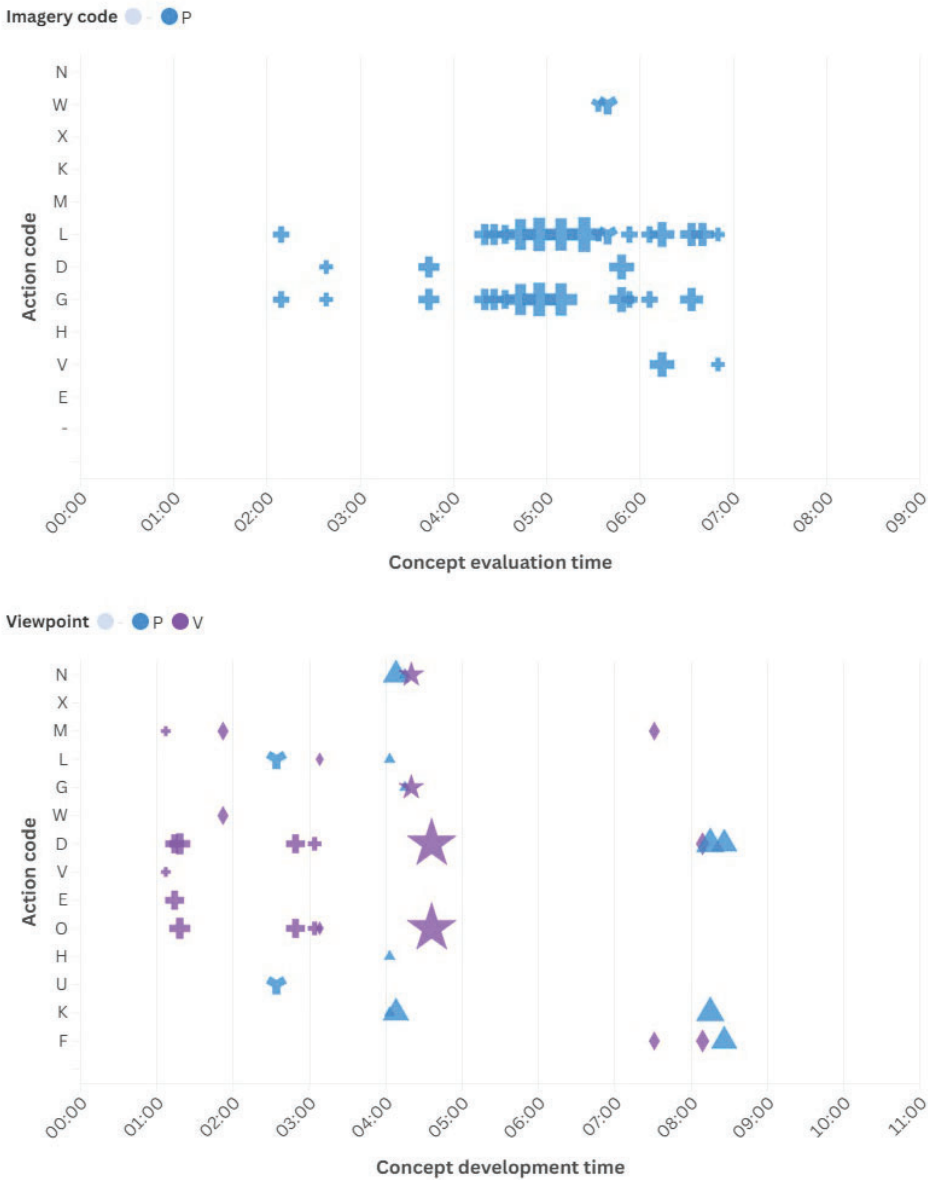


1: Overall design process map



2: Action without imagery map

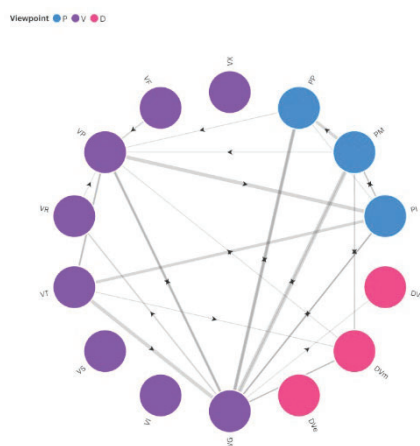




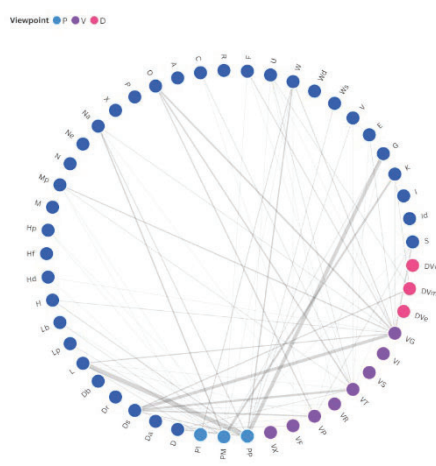
3: Imagery process maps by design stage



4: Overall back links network graph

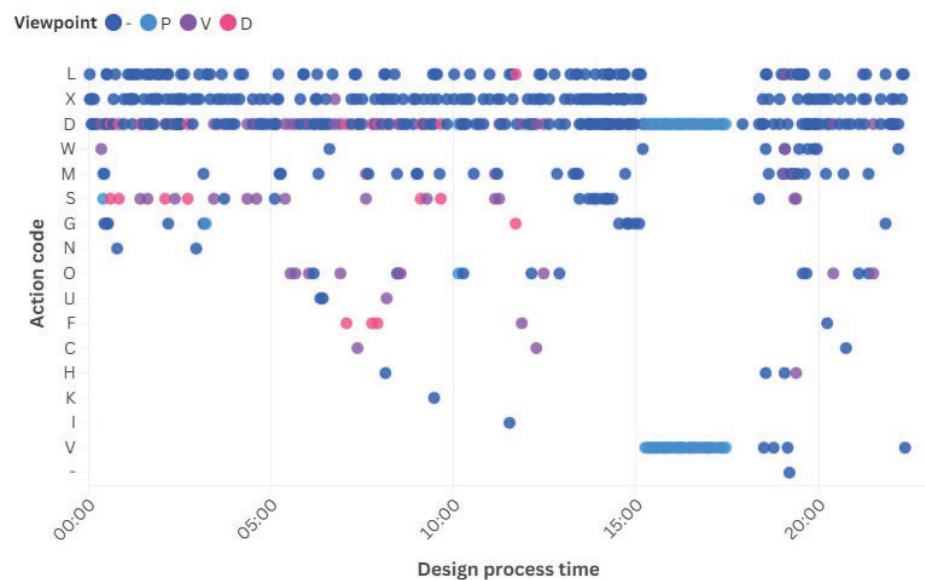


5: Overall other links network graph

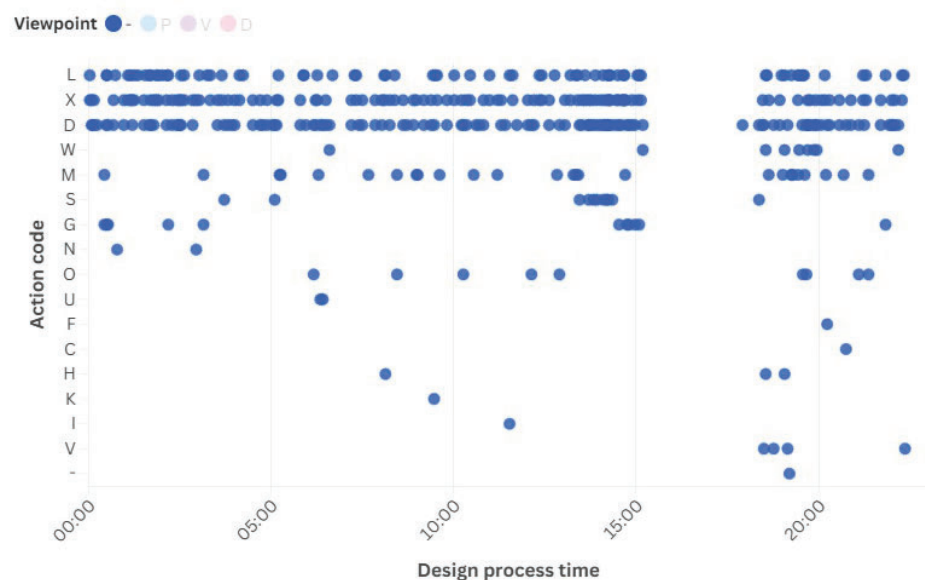


6: Overall imagery-action links network graph

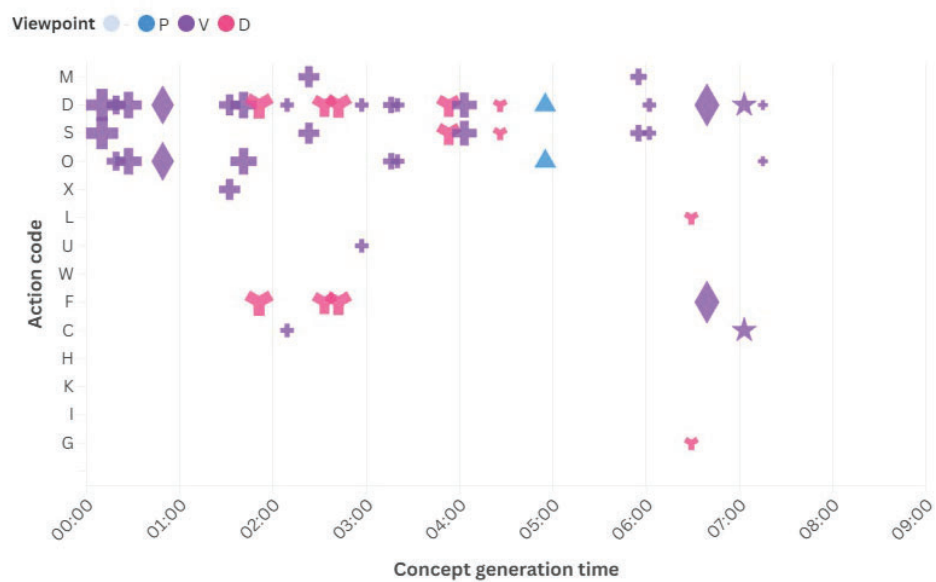
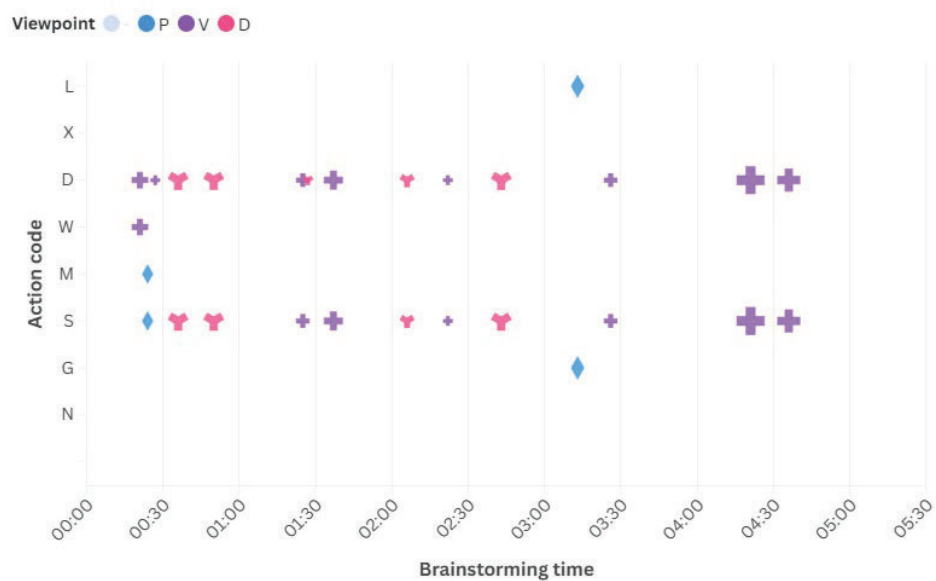
Appendix 20: P-7 full maps and networks for Chapters 8 and 9

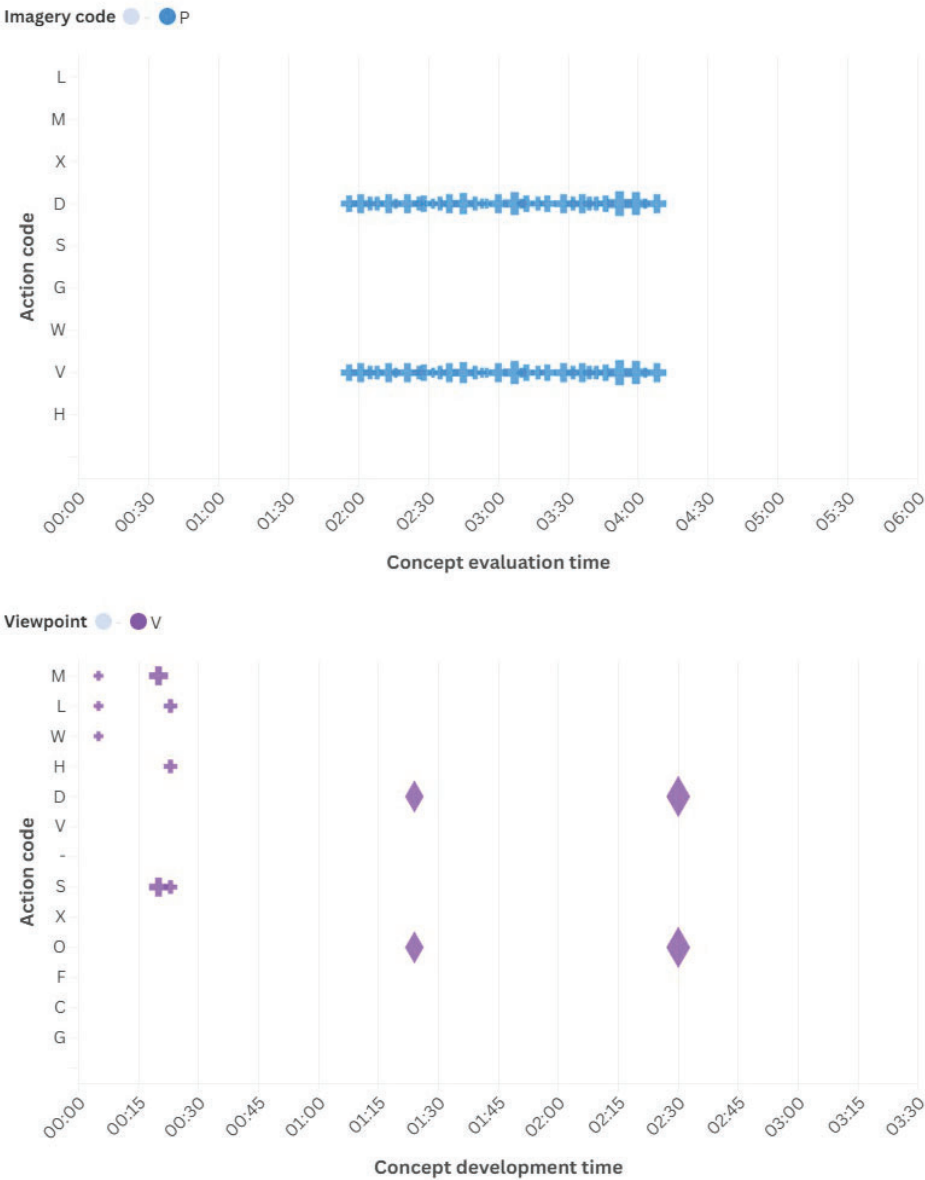


1: Overall design process map

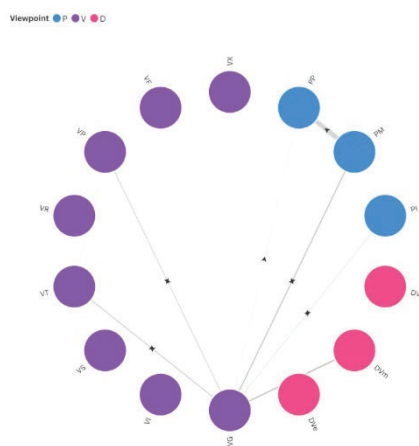


2: Action without imagery map





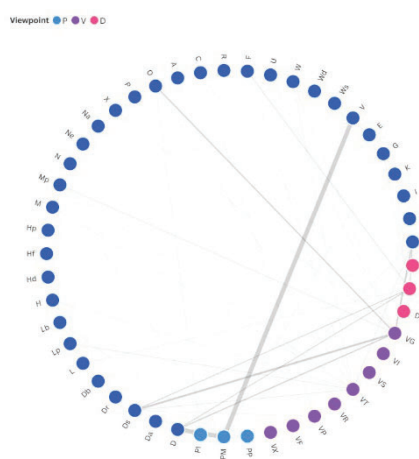
3: Imagery process maps by design stage



4: Overall back links network graph



5: Overall other links network graph

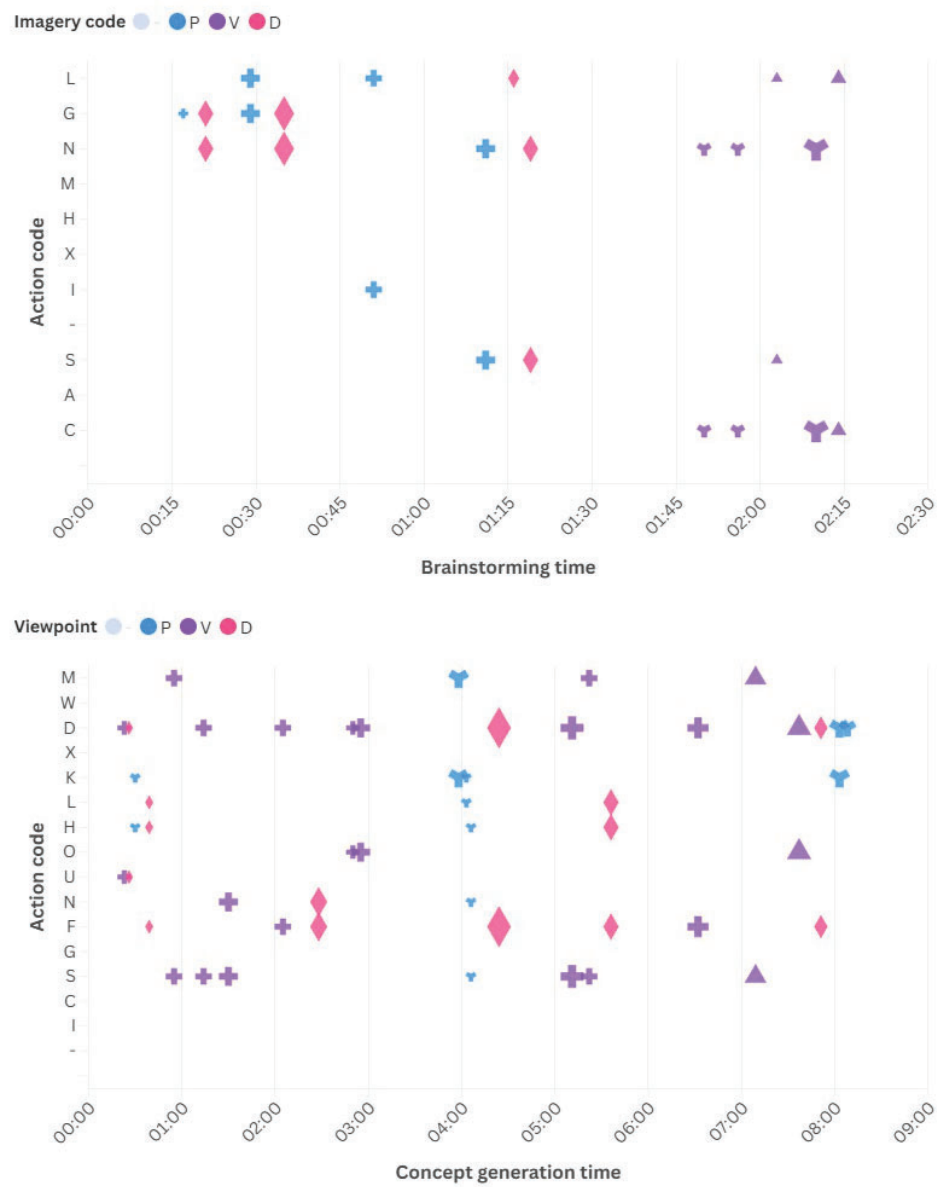


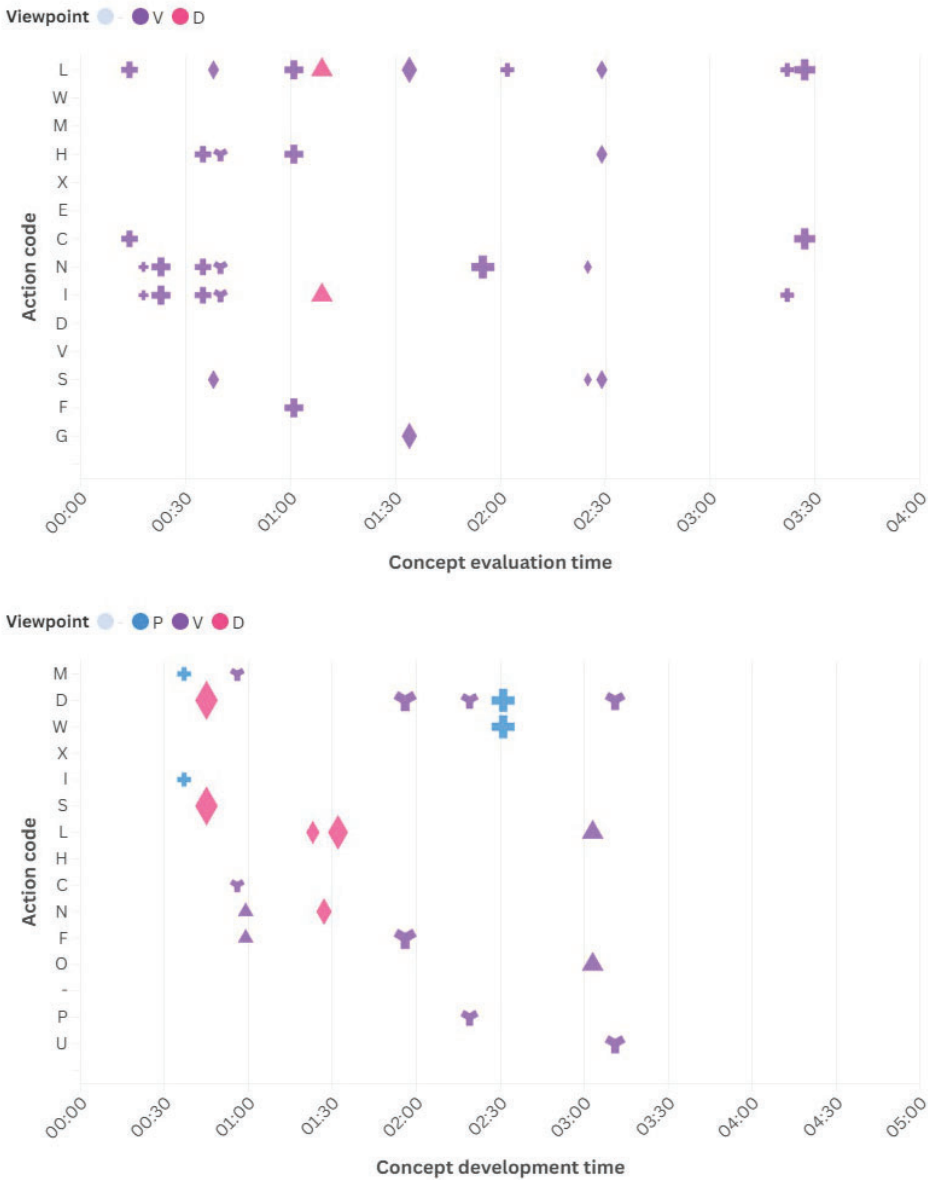
6: Overall imagery-action links network graph

Appendix 21: P-8 full maps and networks for Chapters 8 and 9

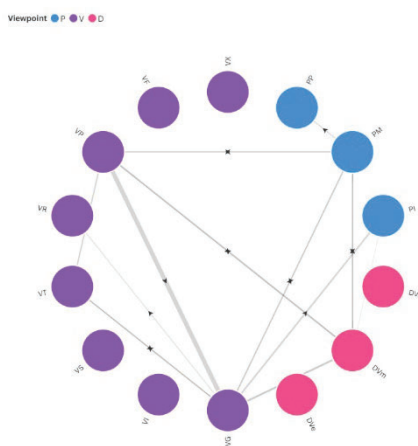


1: Overall design process map

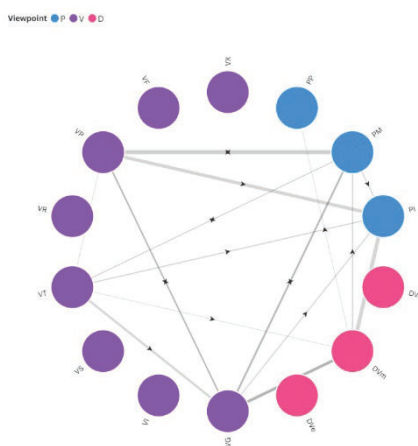




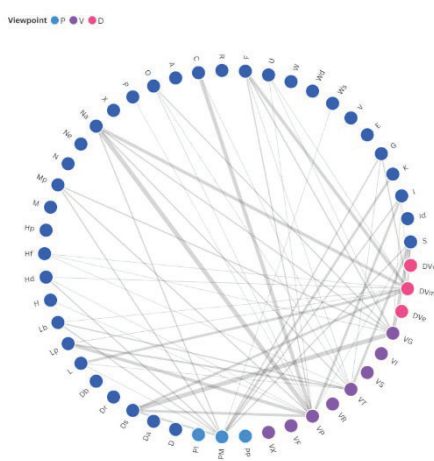
2: Imagery process maps by design stage



3: Overall back links network graph

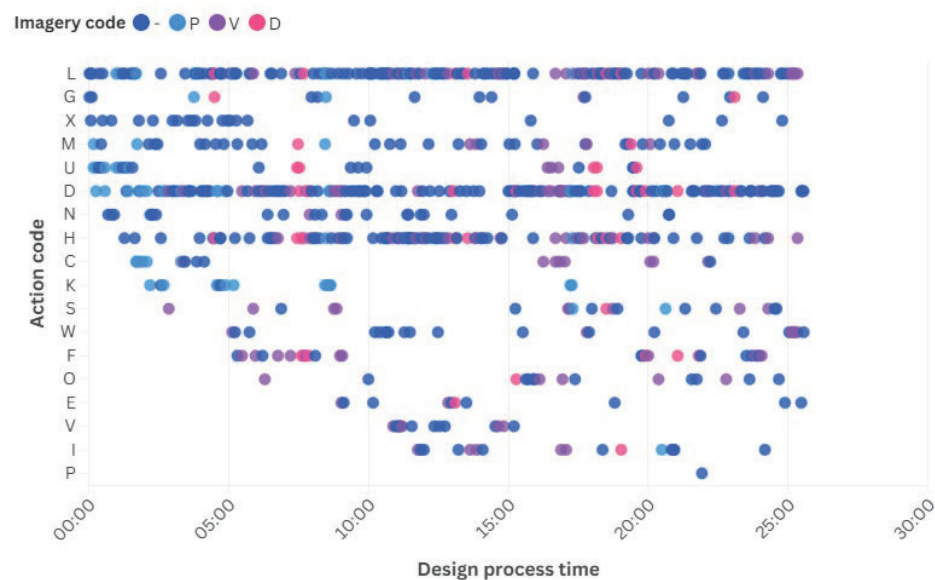


4: Overall other links network graph

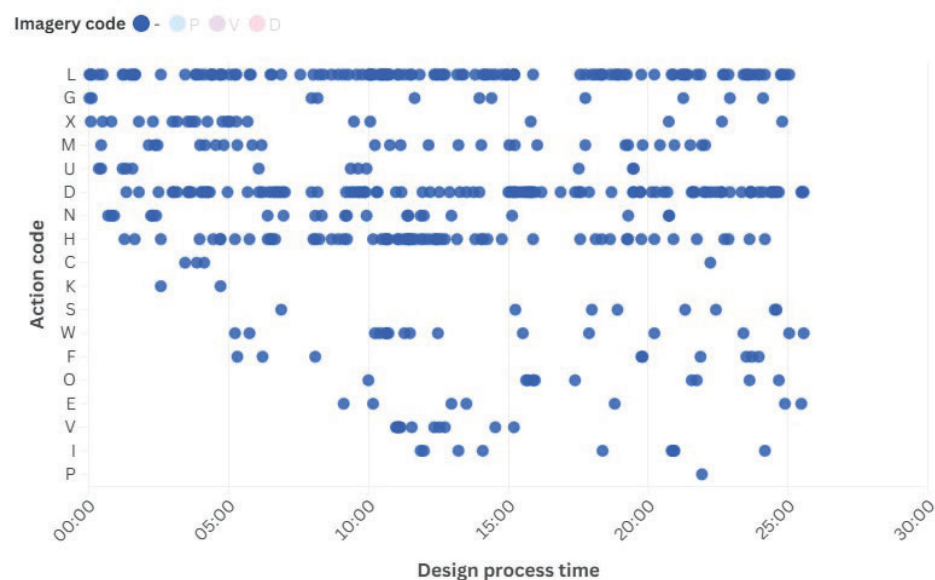


5: Overall imagery-action links network graph

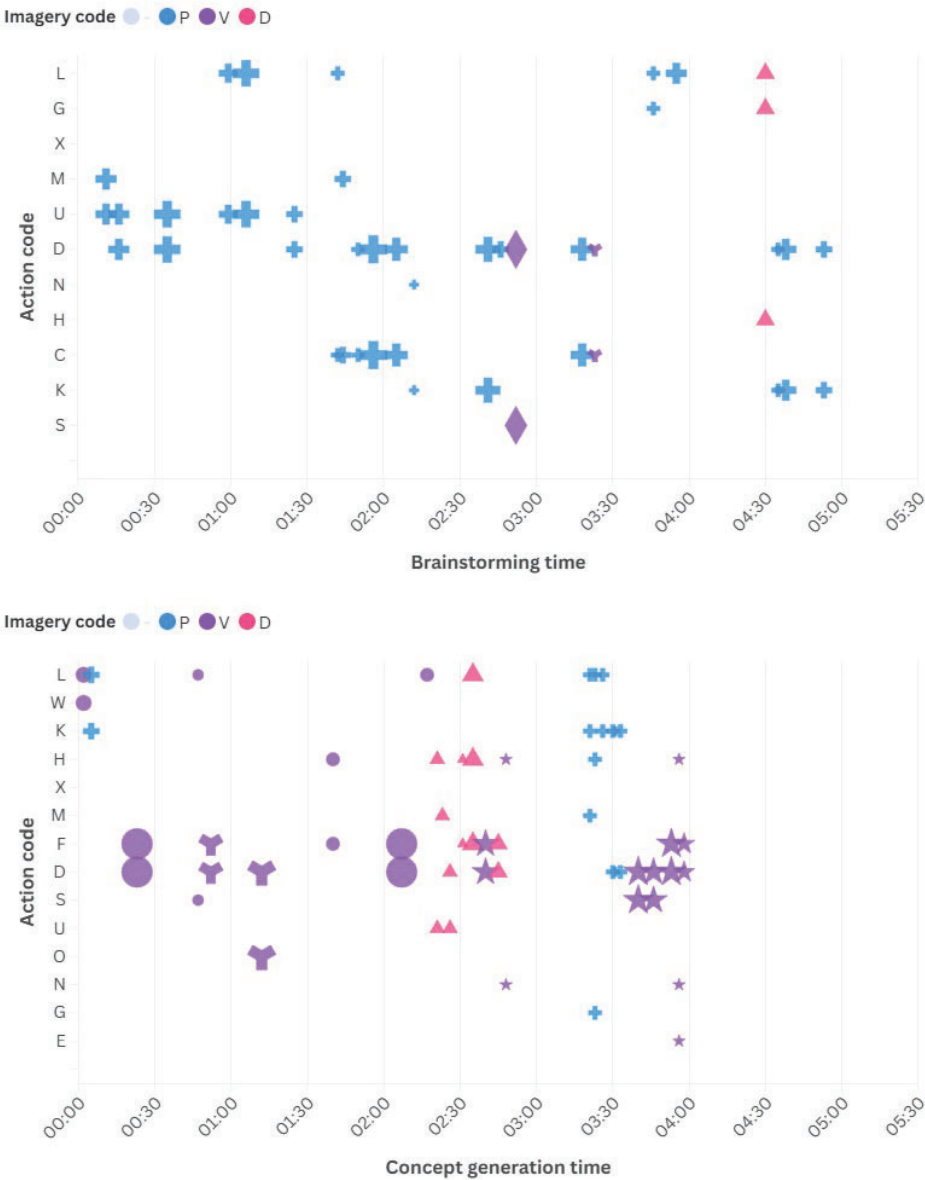
Appendix 22: P-9 full maps and networks for Chapters 8 and 9

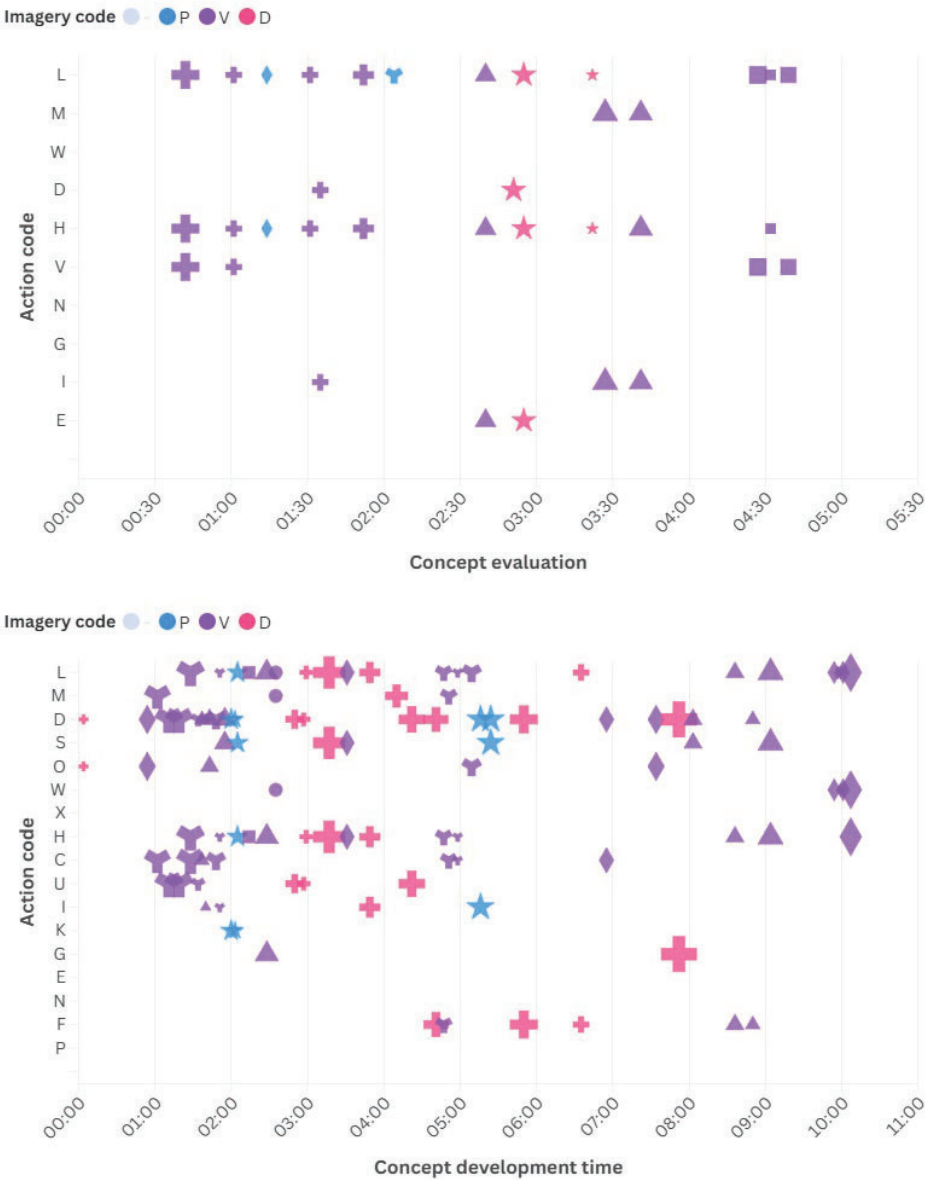


1: Overall design process map

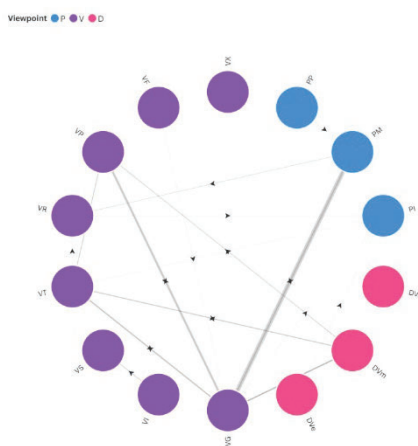


2: Action without imagery map

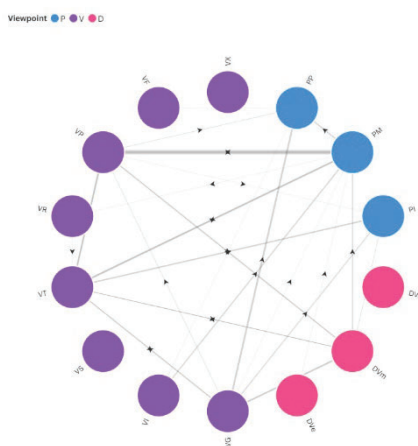




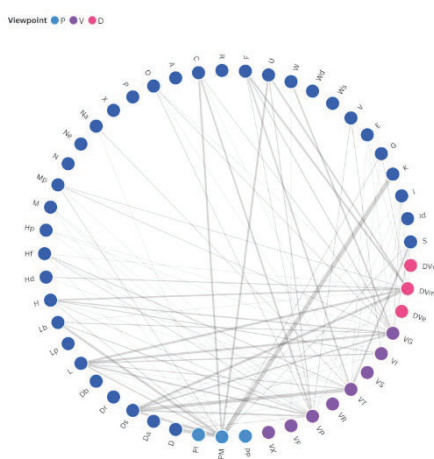
3: Imagery process maps by design stage



4: Overall back links network graph

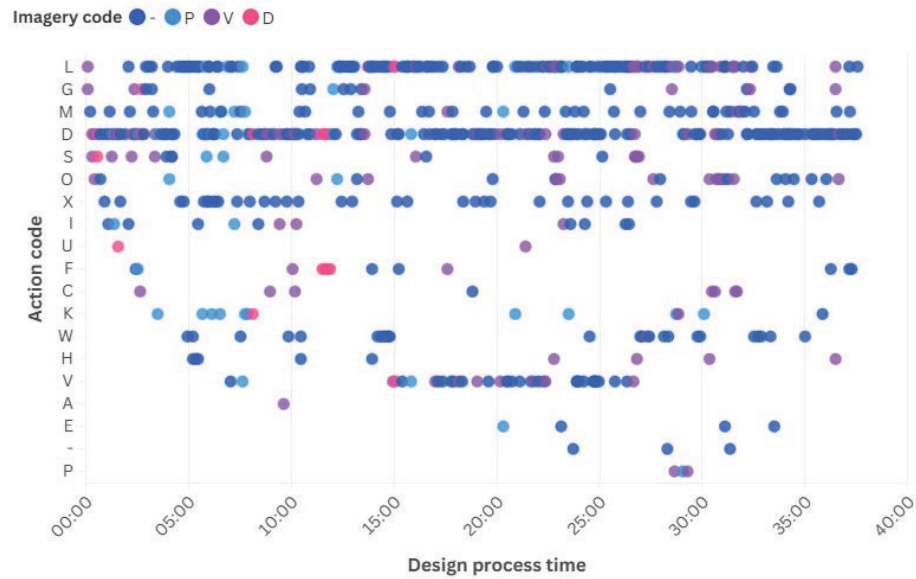


5: Overall other links network graph

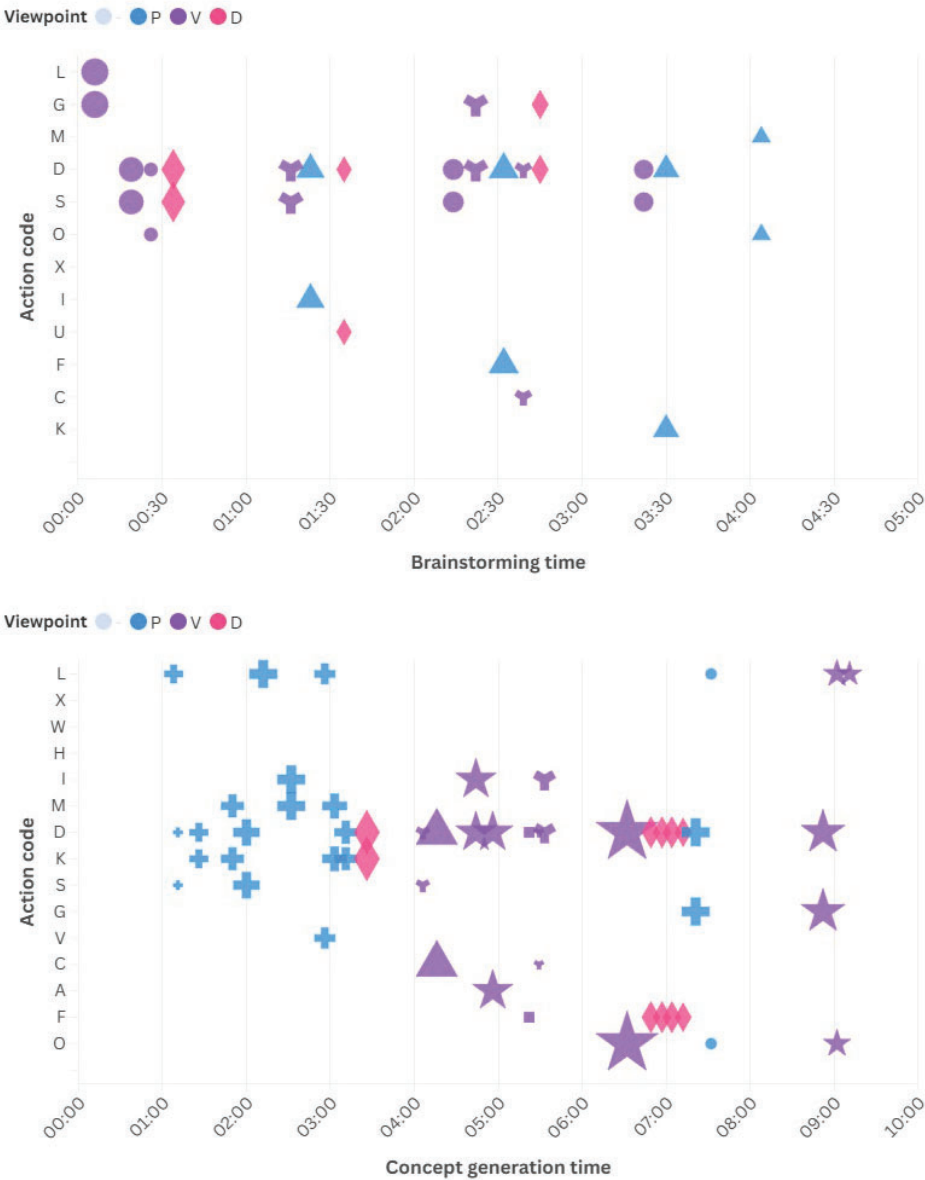


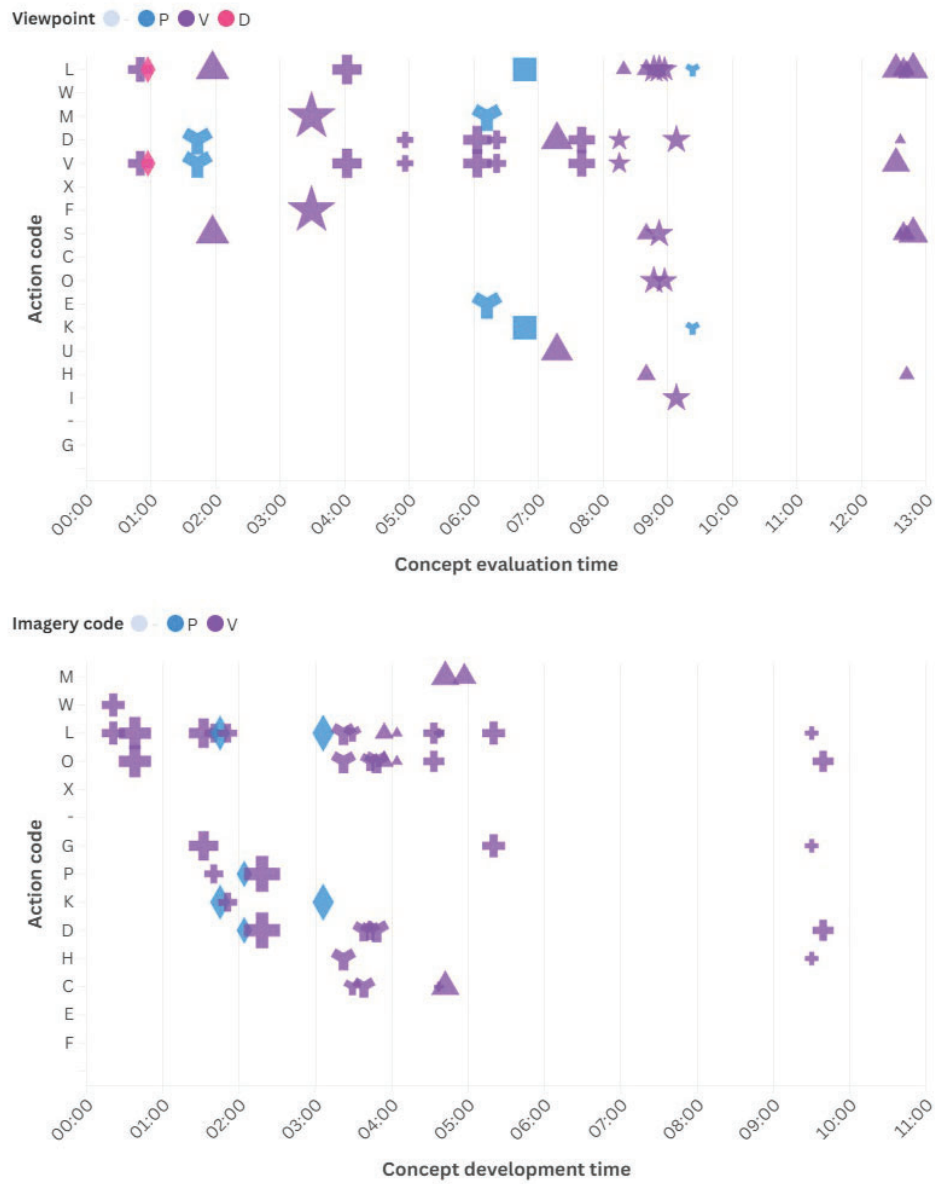
6: Overall imagery-action links network graph

Appendix 23: P-12 full maps and networks for Chapters 8 and 9

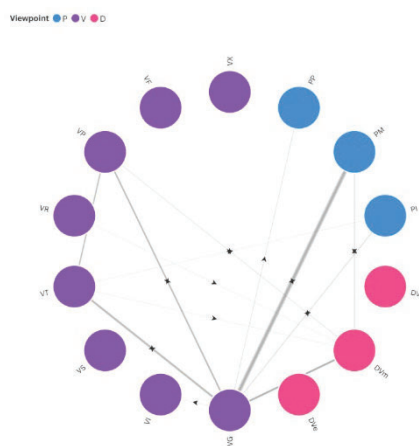


1: Overall design process map

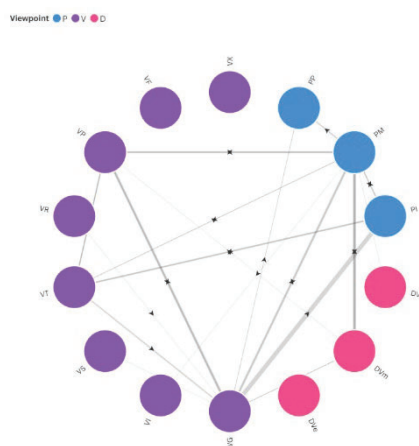




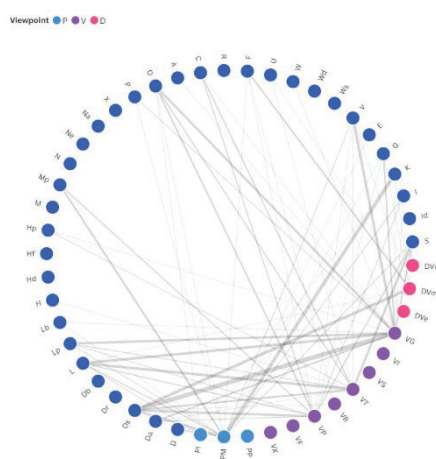
2: Imagery process maps by design stage



3: Overall back links network graph

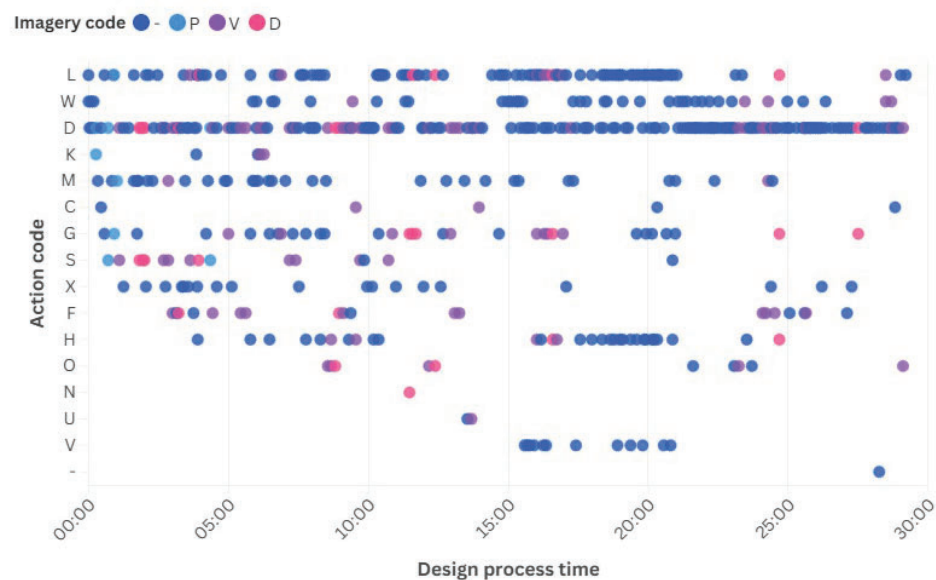


4: Overall other links network graph

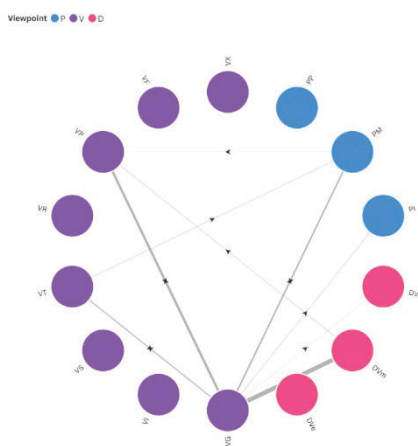


5: Overall imagery-action links network graph

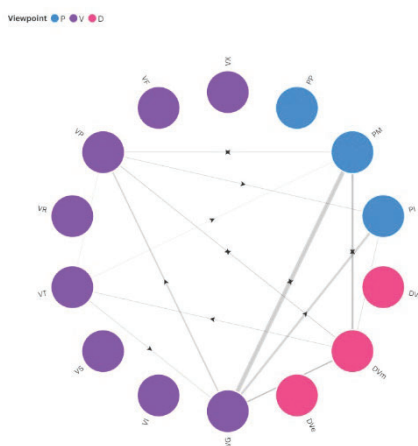
Appendix 24: P-13 full maps and networks for Chapters 8 and 9



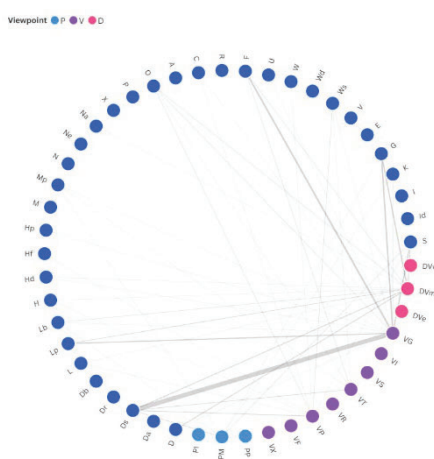
1: Overall design process map



2: Overall back links network graph

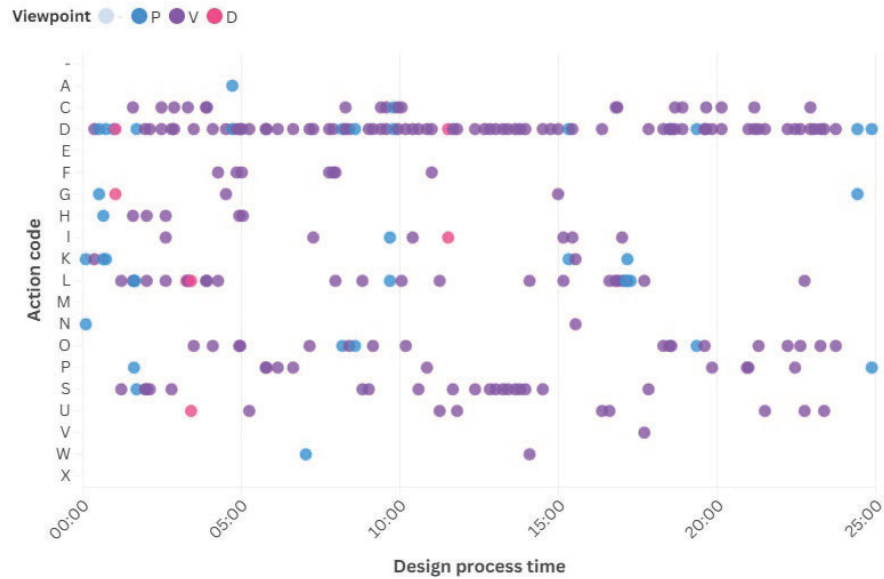


3: Overall other links network graph

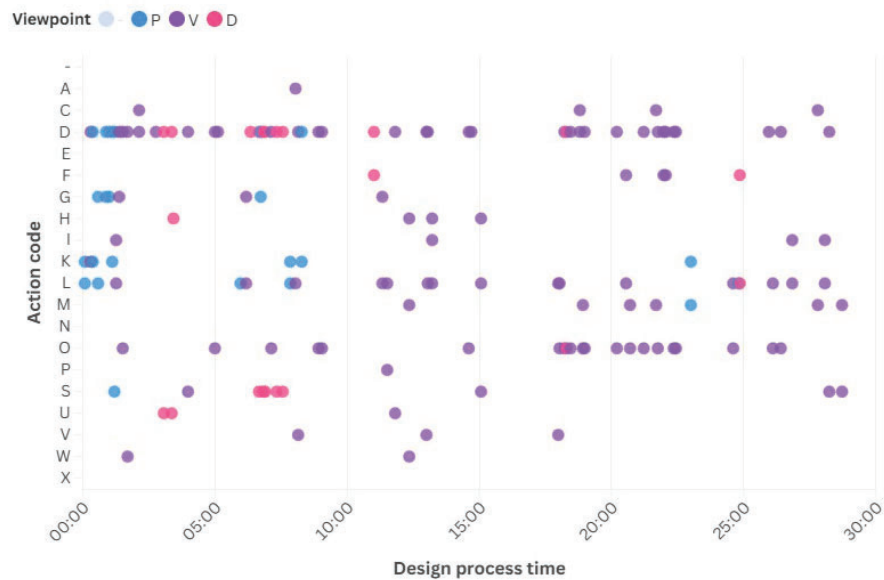


4: Overall imagery-action links network graph

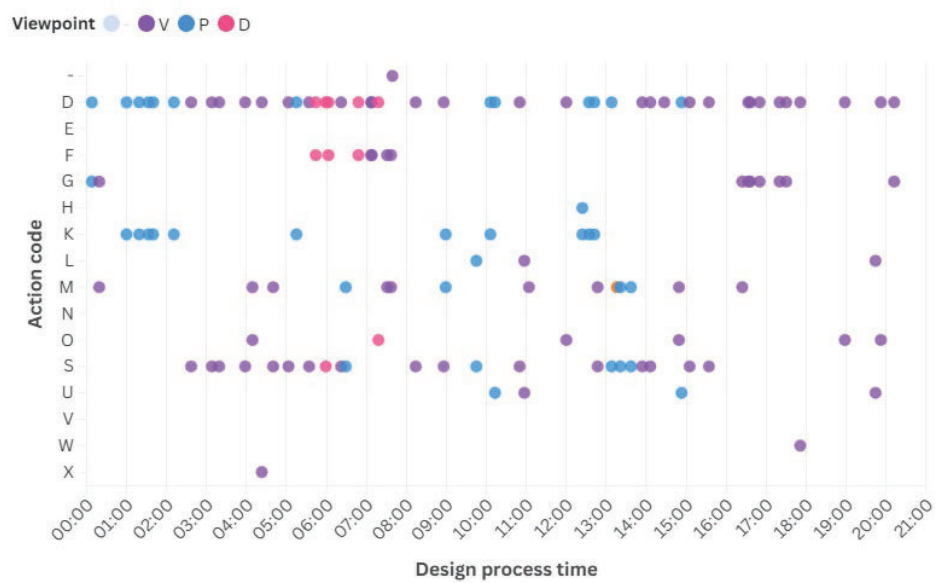
Appendix 25: Alphabetically ordered process maps for Chapters 8 and 9



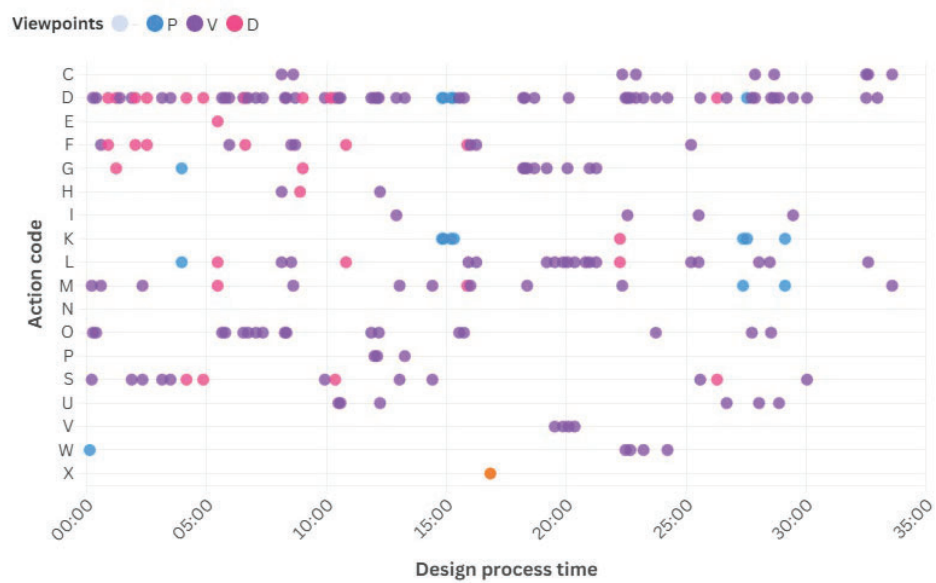
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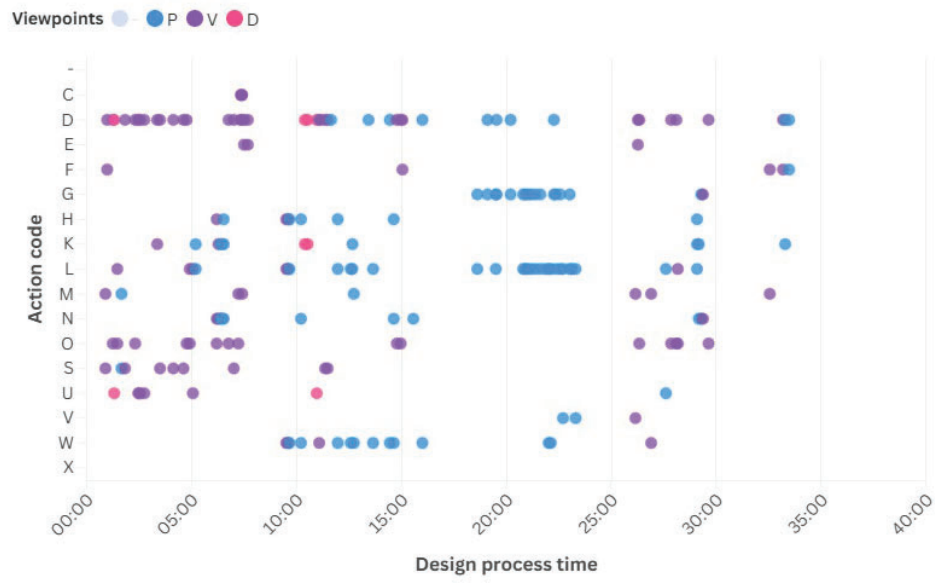
2: P-2



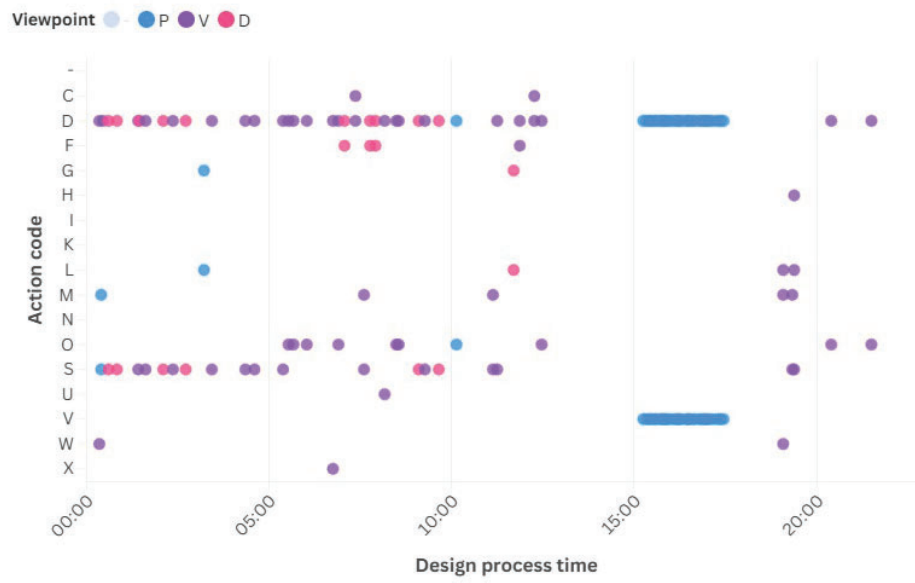
3: P-3



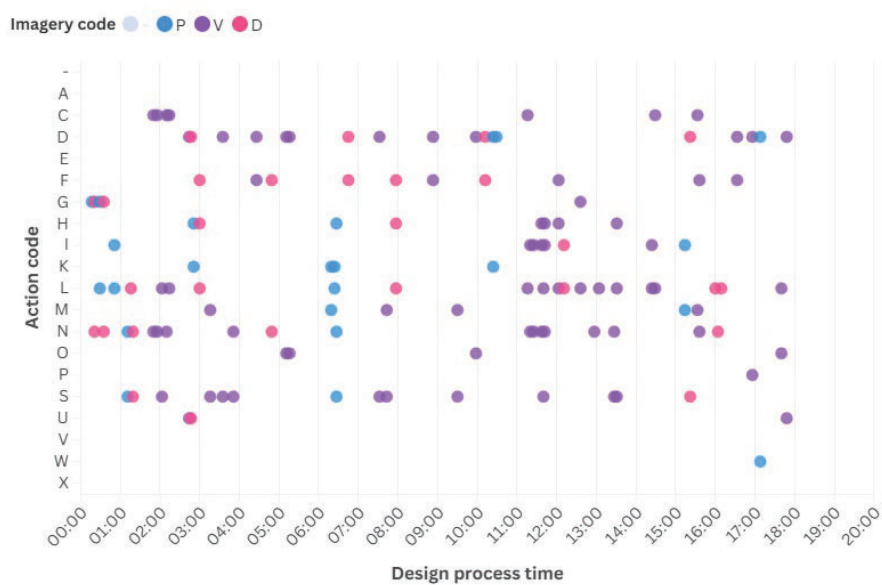
4: P-4



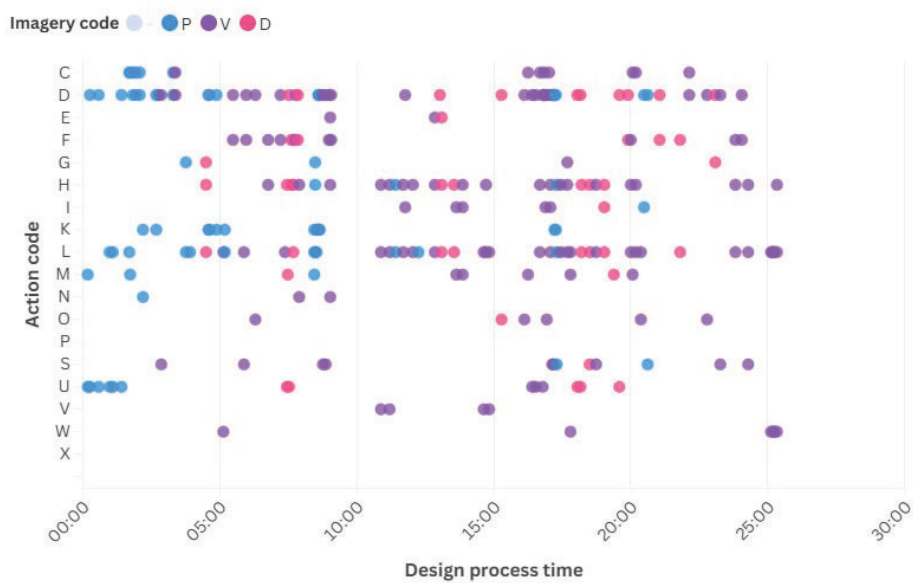
5: P-5



6: P-7



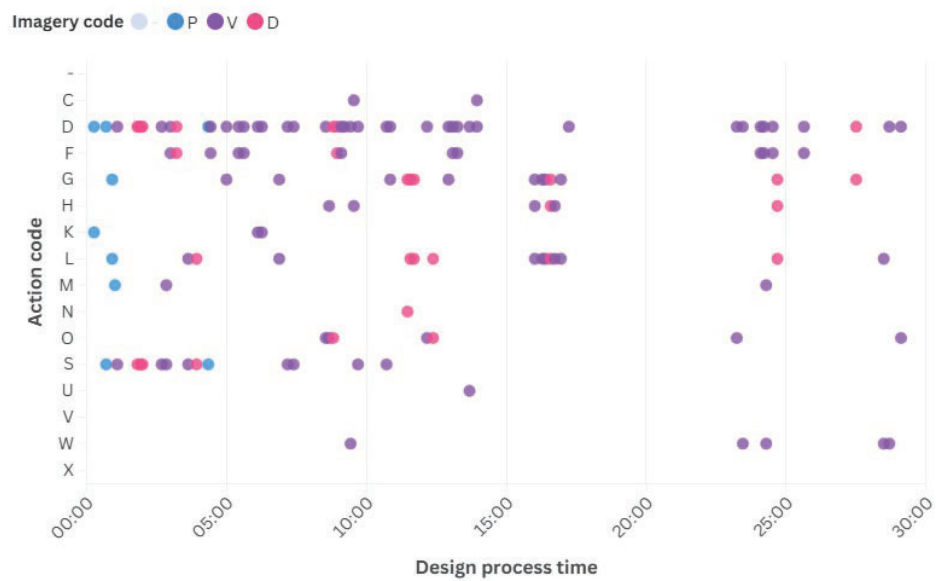
7: P-8



8: P-9



9: P-12



10: P-13

Appendix 26: EVID questionnaire

Experience of Visual Imagery in Design

Mental imagery is the experience of perceiving an image in one's own mind: for example, if I asked you to visualise a horse in a field of yellow flowers in your mind, can you see it? This research project is attempting to specify exactly when and how this occurs within designers during the design process.

The aim of this questionnaire is to provide an understanding of your mental imagery experiences during design thinking.

The survey will take approximately 15 minutes to complete. Please complete all parts on your screen. Varying measurements will be used and these will be detailed to you for each question.

Next ➔

You are invited to take part in this study as part of a wider research project being conducted by Rebecca Macfie for her PhD research at the University of Strathclyde in Glasgow, Scotland. Completion of this questionnaire is voluntary and to opt-out, please email Rebecca via the contact details below. By completing this questionnaire you are giving explicit consent for taking part in the study and for the responses provided to be used for and within research reports for the project. All personal information will be kept entirely confidential and/or anonymised, and will be deleted following successful completion of the project. Please read the information sheet that was attached to the email, and the deadline for completion of the questionnaire is XXX.

If you have any questions, please contact Rebecca Macfie at rebecca.macfie@strath.ac.uk.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

⬅ Back

Next ➔

Please read and respond to the following statement(s) carefully

Tick all that apply

I have read and understand the information, and have had the opportunity to ask questions

☐

I understand that I am free to withdraw from engaging with the study at any time, by closing the browser tab, without giving any reason

☐

⬅ Back

Next ➔

Personal details

Please be advised the details on this page are requested for organisation of the data collected. All information will be kept entirely anonymous and deleted upon completion of the project.

What is your full name?

What is your student email address?

Please provide your student registration number.

What academic year are you currently?

Please select your course from the list below.

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Experience of Visual Imagery in Design

The Experience of Visual Imagery in Design (EVID) questionnaire has been created to measure the mental imagery experience in design. The format of the questionnaire will feature one design task that you are asked to generate entirely within your own mind. Please answer the questions as honestly as you can, and be sure to read the full information for each question to understand how you are expected to respond.

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Section 1

In your mind, generate a concept for a product to encourage gardening while living in a small apartment.

Consider carefully the image of your concept in your mind's eye. How vivid is this image from 0 to 5.

	0 - no image at all	1	2	3	4	5 - as vivid as real life
Vividness	☐	☐	☐	☐	☐	☐

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If participants responded with a “0” rating:

Do you have a concept generated, even if not visually in your mind?

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Next

In your own words, please describe the elements of your generated concept.

In your own words, please describe **how** you have generated a concept.

Back

Next

In your own words and as much detail as possible, please describe how you would usually generate a concept without visual mental imagery.

Selecting next will finish the questionnaire, please make any necessary changes first.

Tick

I have read and understood and I am happy with my responses.

☐

Back

Next

For ratings “1” to “5”:

In your own words, please describe the *elements* of your generated concept.

Please detail the **form** of your image of your generated concept.

	2D	3D	Sketch	Photographic	Memory	Other
Form	☐	☐	☐	☐	☐	☐

If you selected “other”, please detail (mark x if other not selected).

[Back](#) [Next](#)

How difficult was it to generate this concept in your mind from 1 to 5, with 1 being very difficult and 5 being very easy?

1	2	3	4	5
---	---	---	---	---

Did you intentionally generate the visual image in your mind, rather than it occur instantaneously?

Did you use memory to assist in your concept generation?

[Back](#) [Next](#)

How vivid are the images of any memories that assisted your concept generation, from 0 to 5?

	0 - no image at all	1	2	3	4	5 - as vivid as real life
Vividness	☐	☐	☐	☐	☐	☐

How difficult was it to visualise these memories from 1 to 5, with 1 being very difficult and 5 being very easy?

1	2	3	4	5
---	---	---	---	---

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Did you use imagination to assist in your concept generation?

[Back](#)[Next](#)

How vivid are the images from imagination that assisted your concept generation, from 0 to 5?

	0 - no image at all	1	2	3	4	5 - as vivid as real life
Vividness	☐	☐	☐	☐	☐	☐

How difficult was it to visualise these imagination images from 1 to 5, with 1 being very difficult and 5 being very easy?

1	2	3	4	5
---	---	---	---	---

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Section 2

In your mind, inspect, scan and/or evaluate your generated concept for missing details or necessary changes.

Consider carefully the image of your concept in your mind's eye. How vivid is this new image from 0 to 5.

	0 - no image at all	1	2	3	4	5 - as vivid as real life
Vividness	☐	☐	☐	☐	☐	☐

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For sections 2-5, all following questions were the same as for Section 1.

Section 3

In your mind, transform your generated concept to account for any changes that are required.

Consider carefully the image of your concept in your mind's eye. How vivid is this new image from 0 to 5.

	0 - no image at all	1	2	3	4	5 - as vivid as real life
Vividness	☐	☐	☐	☐	☐	☐

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Section 4

In your mind, rotate your generated concept to visualise a new angle.

Consider carefully the image of your concept in your mind's eye. How vivid is this new image from 0 to 5.

	0 - no image at all	1	2	3	4	5 - as vivid as real life
Vividness	☐	☐	☐	☐	☐	☐

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Section 5

In your mind, visualise the wider space that your product is situated in.

Consider carefully the image of your concept in your mind's eye. How vivid is this new image from 0 to 5.

	0 - no image at all	1	2	3	4	5 - as vivid as real life
Vividness	☐	☐	☐	☐	☐	☐

[Back](#)[Next](#)

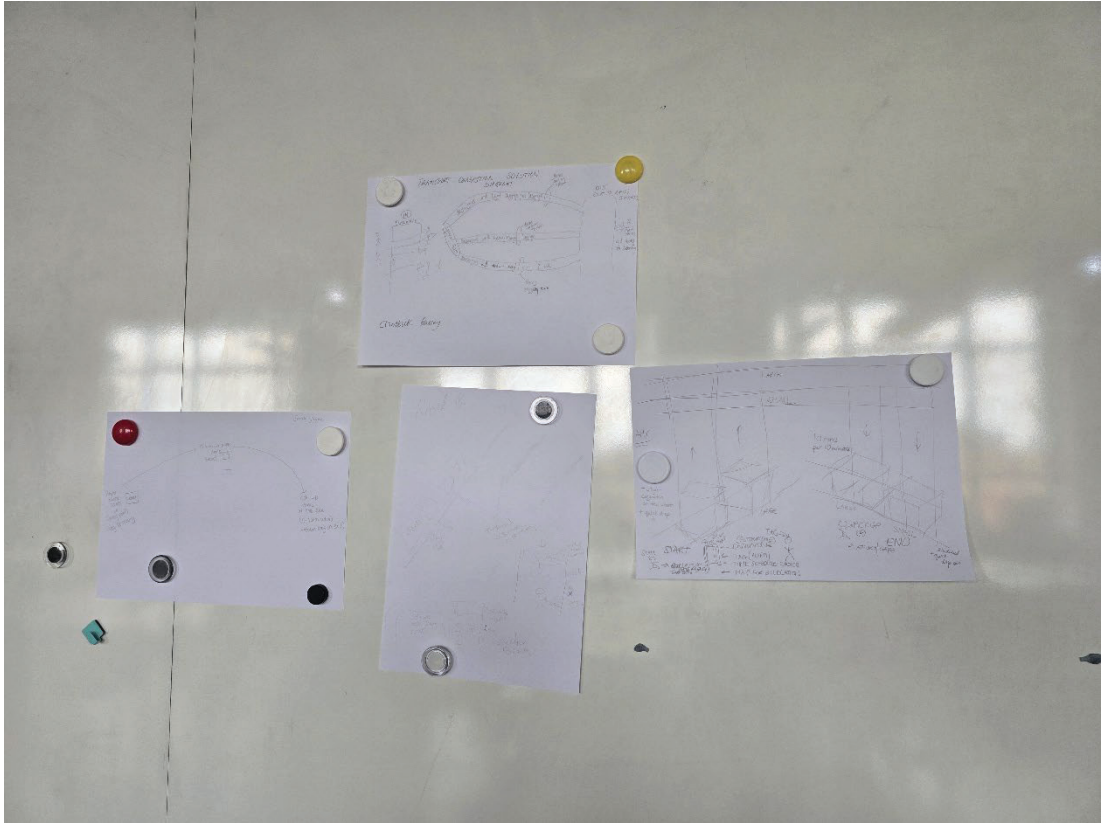
Appendix 27: Workshop proposal for E&PDE 2025

27TH INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
11-12 SEPTEMBER 2025, UNIVERSITY OF MALTA, MALTA

E&PDE 2025 Workshop Proposal	
Workshop title:	Supporting Diversity of Learning in Design Education: The Role of Mental Imagery in Creativity and Innovation
Name of chairs:	Rebecca Macfie; Ian Marcus Edgecomb; Dr Ross Brisco
Description of activities and expected outcomes:	
Mental imagery is defined as perceiving an image within one's mind (Macfie <i>et al.</i>, 2023). Recent research suggests that mental imagery can enhance the design process through the creative outputs of design students (Edgecomb <i>et al.</i>, 2024; Macfie <i>et al.</i>, 2023; Tedjosaputro <i>et al.</i>, 2018), yet there remains a gap to incorporate this state-of-the-art research into educational interventions. This workshop aims to understand how mental imagery can be integrated into education. Participants will be asked how we can adapt teaching and assessment to encompass different mental imagery experiences, enabling learning for all, and will leave with an understanding of why they need to better support this diversity of learners and a framework for how to do this. This workshop will explore the practicality and advantages of utilising cognitive processes in the teaching and assessment of the design process, with a focus on the experience of mental imagery using a variety of design research tools including the newly developed D-LAD framework. It is expected that participants will be from across the education sector with an interest in both design cognition and engineering education. We will be taking a collaborative approach to the workshop, with participants grouped into teams of 4 or 5 and asked to undertake two separate activities: the first will be completing a Lotus method sharing their views on the advantages, challenges and solutions of implementing mental imagery in design education, and the second will be a team design task using a potential tool for implementing mental imagery in design education. Through this collaborative approach, we expect to gather a wider range of views and solutions to the topic, and for the participants to benefit from the opportunity to have discussions with their peers.	

Timeline of activities (max 3 hours):	
2pm: Introductory lecture covering design cognition research, with a focus on mental imagery	
2.30pm: Activity 1 – team Lotus method looking at the advantages, challenges and solutions of implementing mental imagery in design education	
3pm: Discussion and sharing of ideas in a larger Lotus grid	
3.15pm: Break	
3.30pm: Mini follow-up lecture looking at potential solutions, methods and tools	
3.45pm: Activity 2 – group design task using a potential tool or method for implementing mental imagery in design education	
4.25pm: Discussion and sharing of ideas	
4.45pm: Conclusions	
Necessary equipment in the room:	
• Large whiteboard, pens & eraser • AV-HDMI/projector • Desks laid out for group discussions (4 or 5 per group)	
Maximum number of participants:	20-30
Alignment with conference topic (please tick):	
Novel assessment methods for multidisciplinary team-based students' engineering design projects.	X
Challenges and opportunities for educators to foster human-centred product-service systems (PSS).	
Exploitation of systems design methods in product service systems education.	
Fostering circular economy principles through engineering design educational methods.	
Educating students in considering ethical and social issues in product service systems development.	
Integrating user experiences in different life phases of products and services.	
Innovative approaches promoting sustainability principles in PSS.	
Collaborative design education practices fostering multi-user, multi-perspective products and services.	X
Human-centred product-service system design education in the AI era.	
Industry and academia collaborative models for fostering smart products and services.	
Migration of students from the private sector to government and NGOs – impact on the development of PSS.	
Please return your completed document to:	
[Redacted]	

Appendix 28: LeoCon pilot team sketches



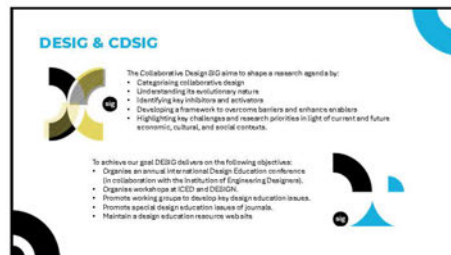
Appendix 29: E&PDE workshop slides



1



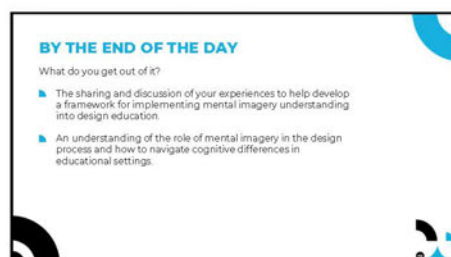
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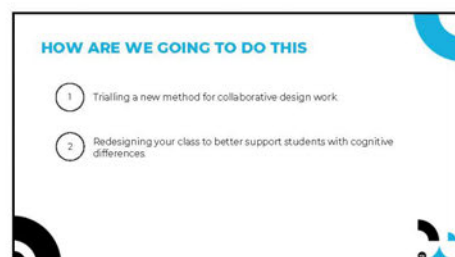
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5



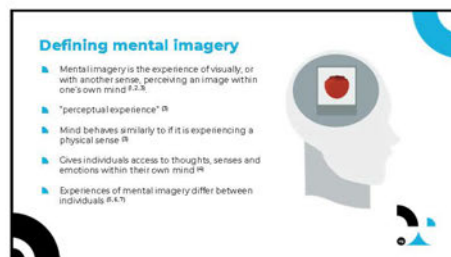
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7



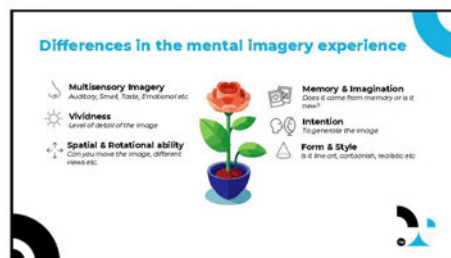
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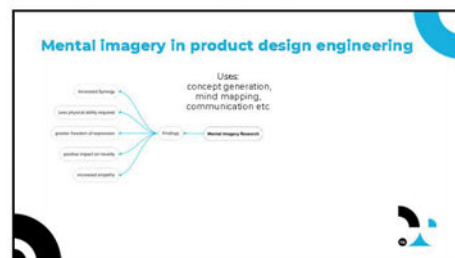
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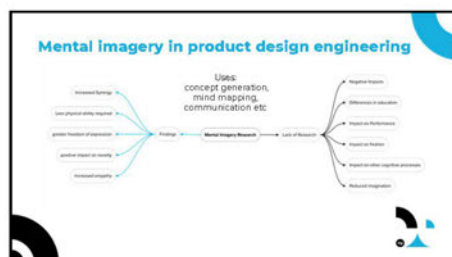
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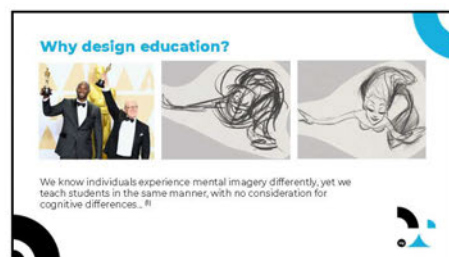
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12



13



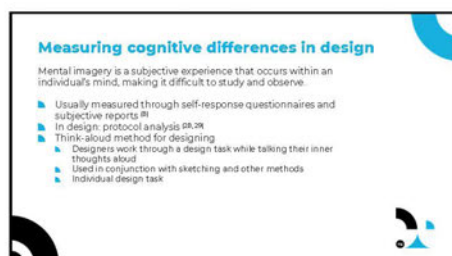
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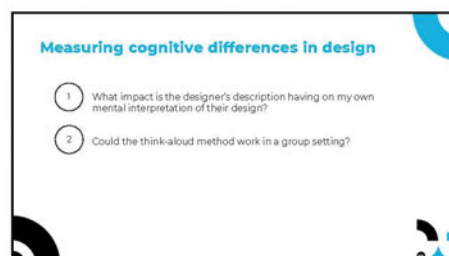
15



16



17



18

The Sit On Your Hands method

 Complete this as a team

Come up with a solution to a design brief, as a team, through discussion alone.

- No form of physical design at all, be it sketch, note-writing, hand gestures...
- Sit on your hands!

19

The Sit On Your Hands method

 Complete this as a team

35 minutes to develop one final design solution as a team

- Discussion only
- No physical form of design – sit on your hands!
- At the end, can one team member write down exactly what your team's final design is.

20

Now, sketch!

 Complete this individually

10 minutes to sketch what you are visualising in your head!

- No team input or sharing of ideas – this should be your interpretation only!
- DO NOT SHARE THE SKETCHES WITH OTHER TEAM MEMBERS

21

BREAK

See you back here at 15:40



22

Welcome Back!

Please take this time to share your sketches with other team members



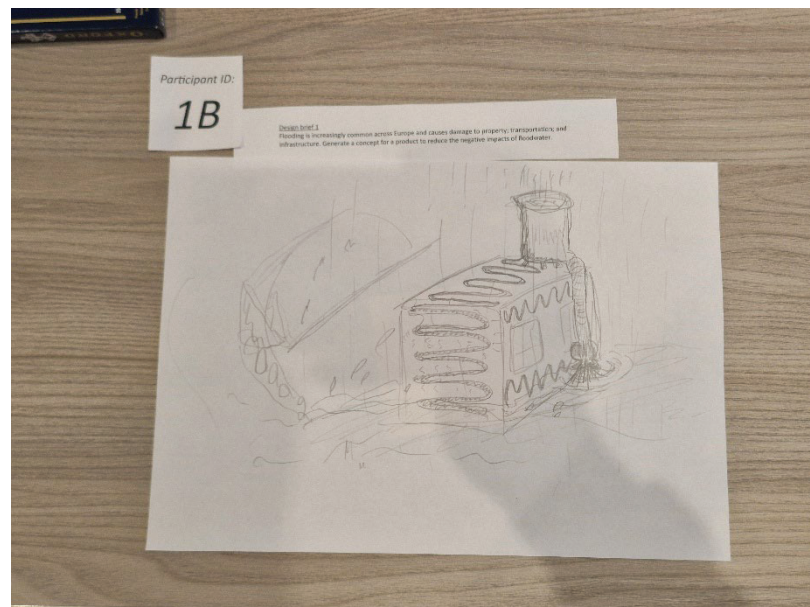
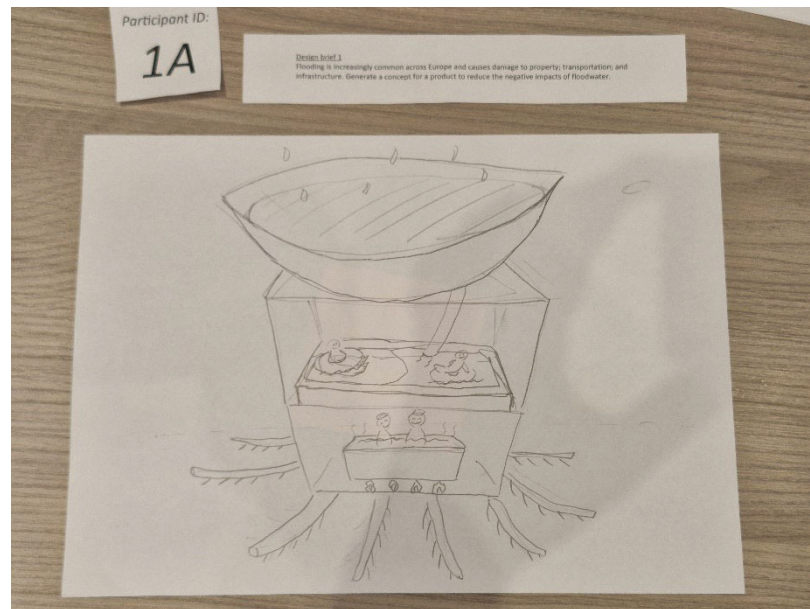
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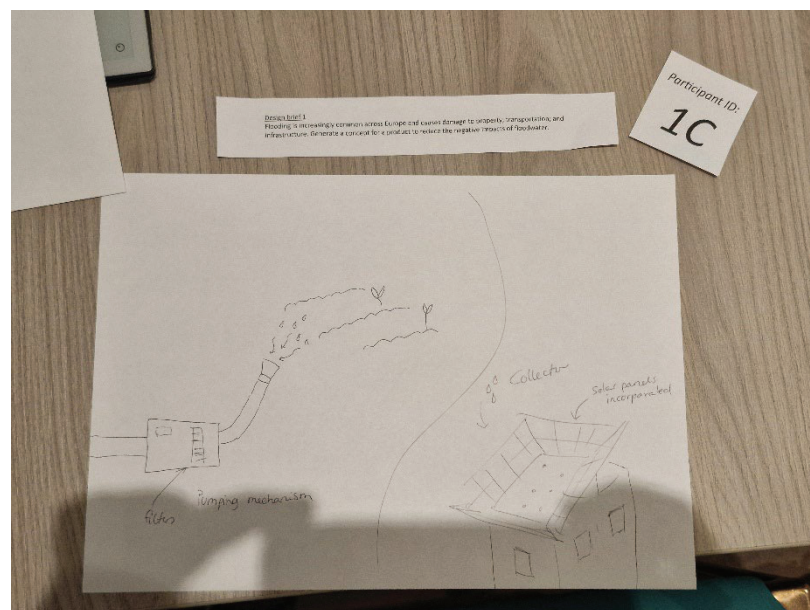
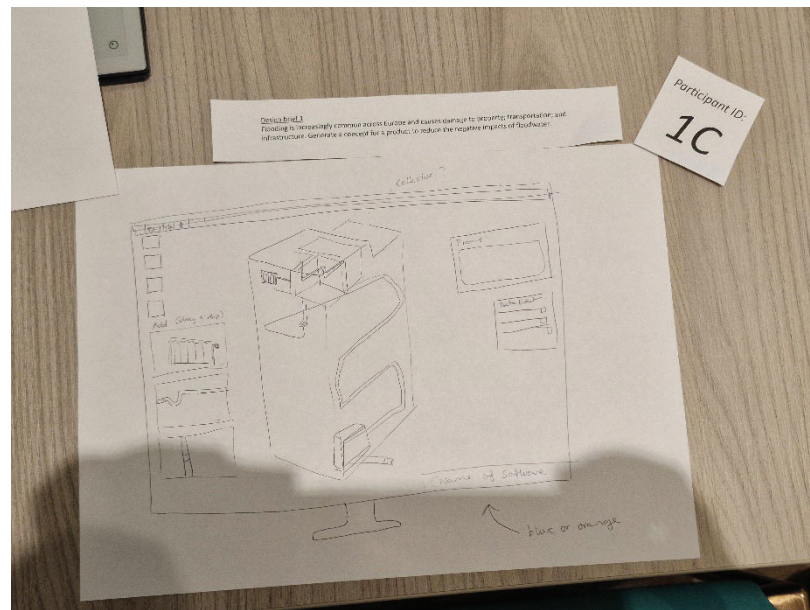
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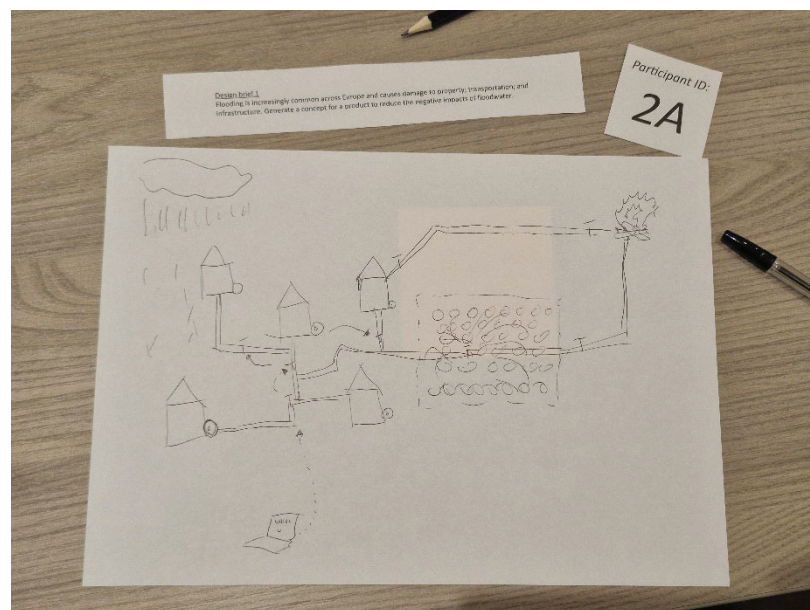
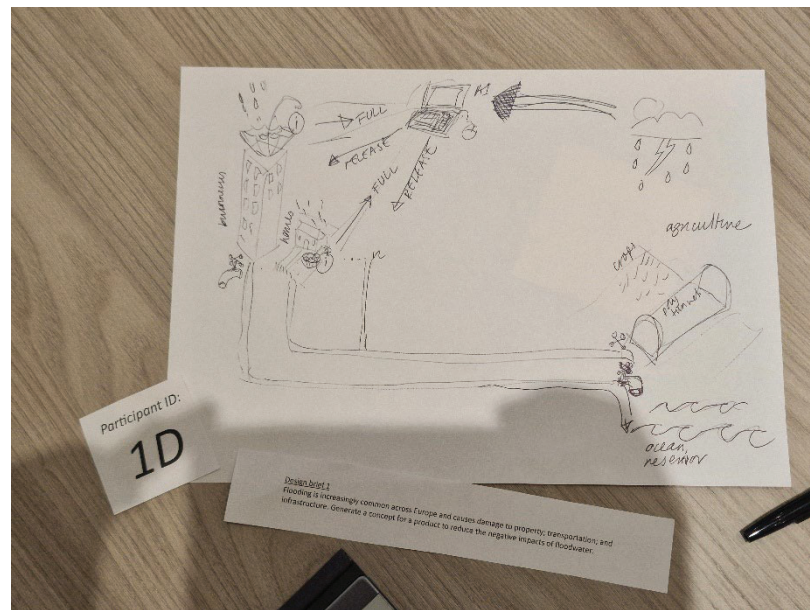


24

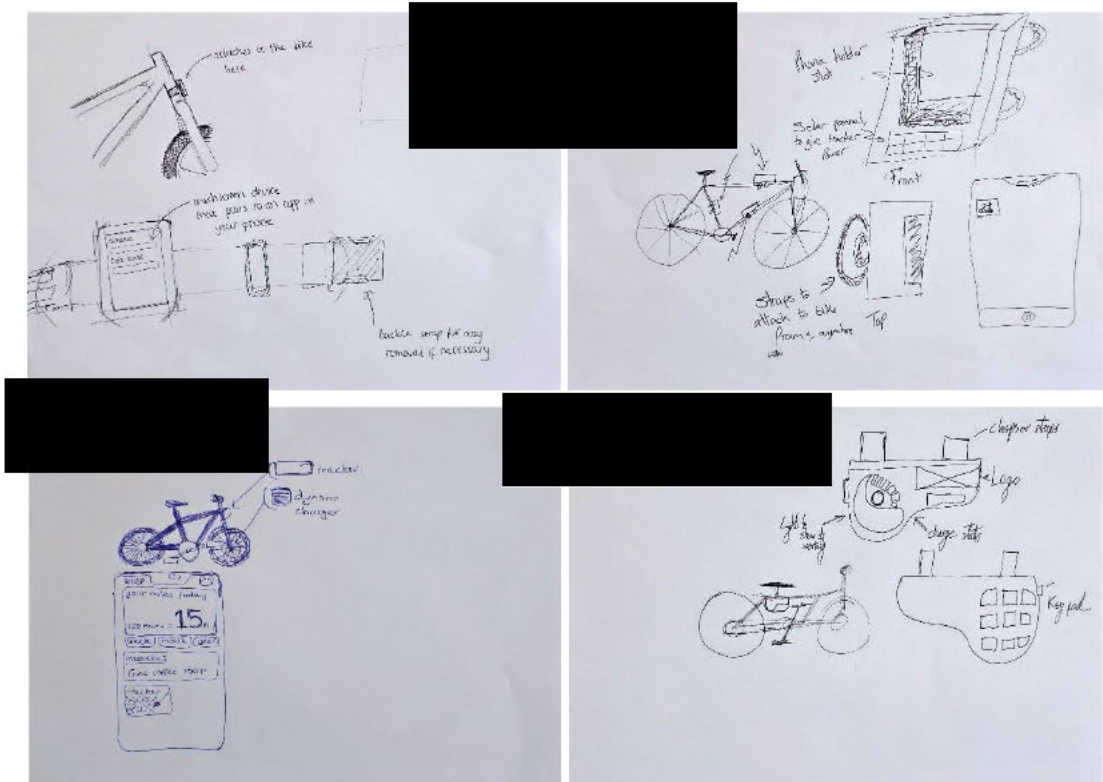
Appendix 30: E&PDE workshop sketches



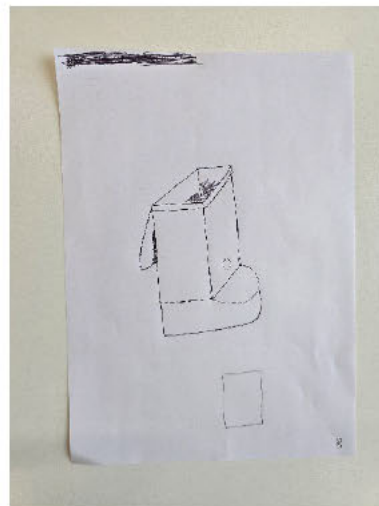




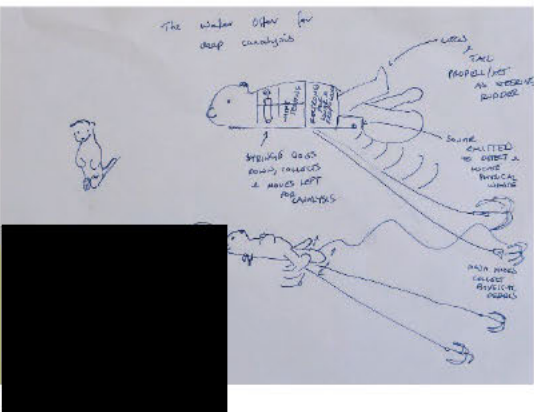
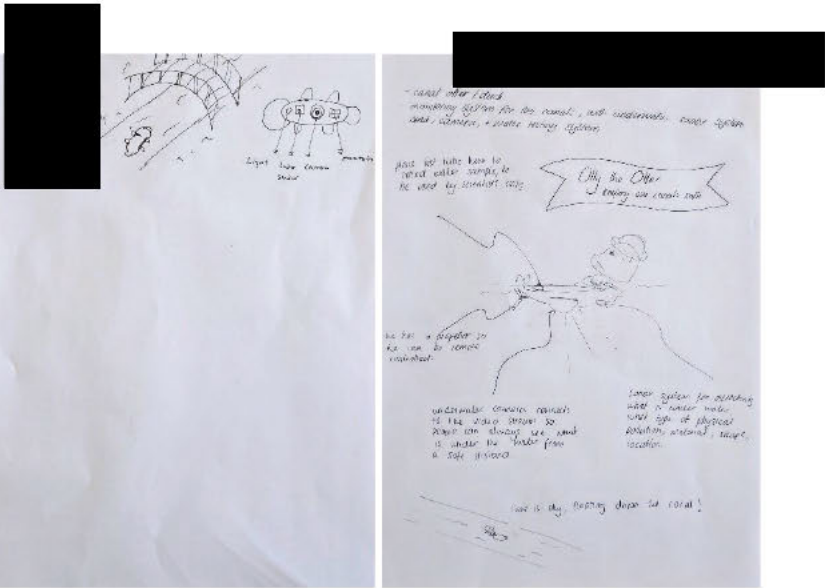
Appendix 31: DM200 SoYH sketches



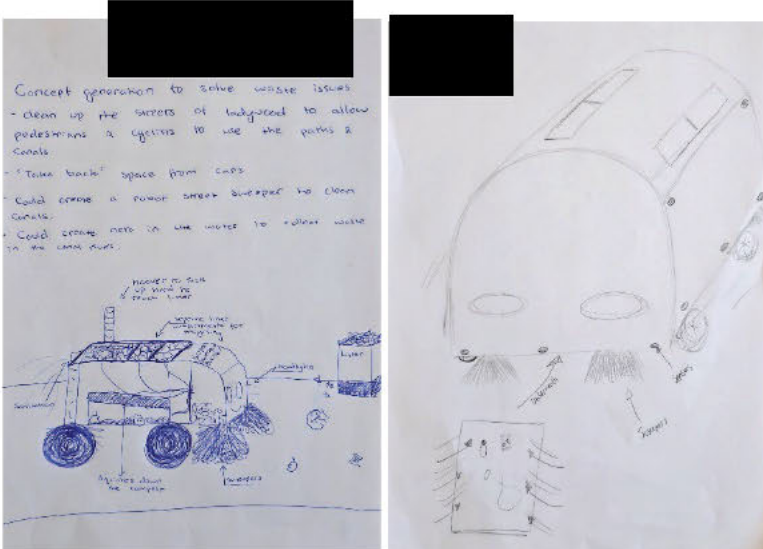
1: Team A



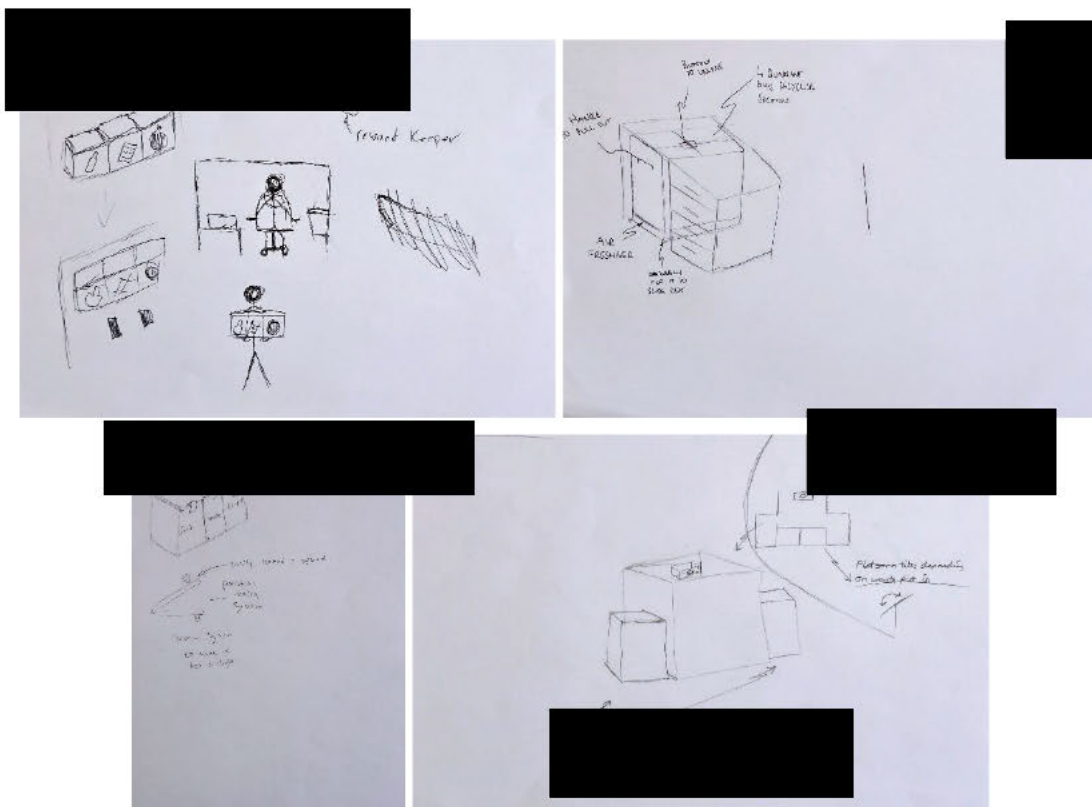
2: Team B



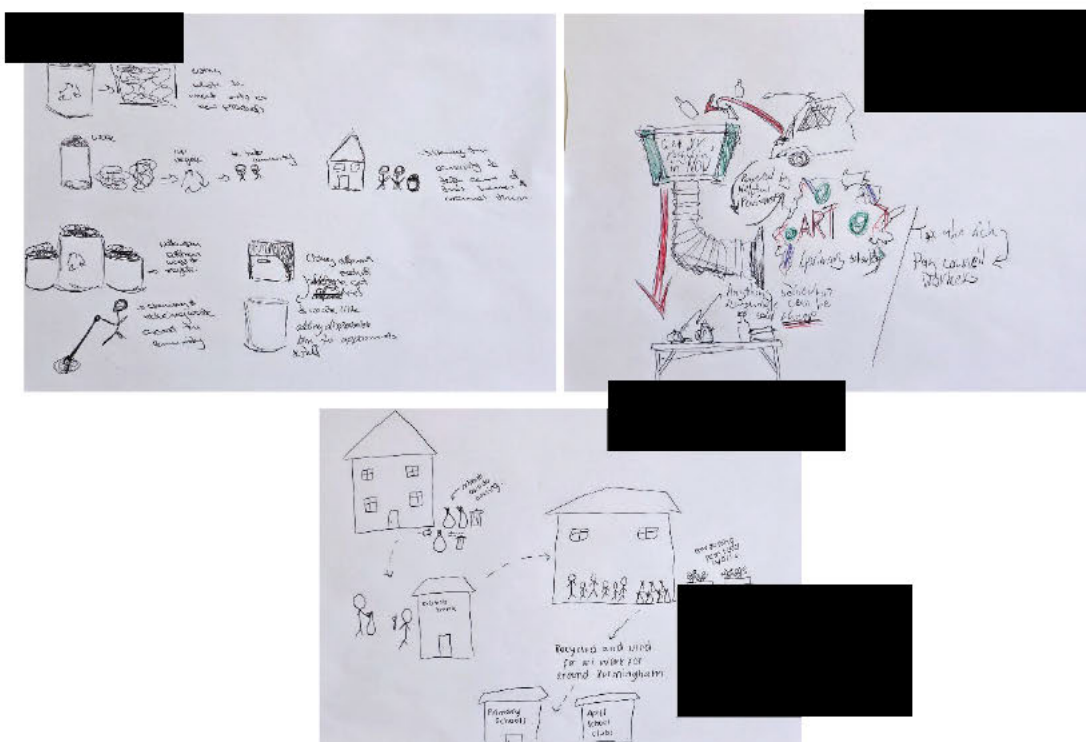
3: Team C



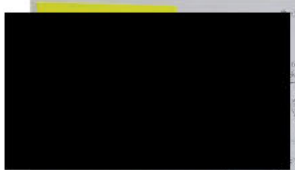
4: Team D

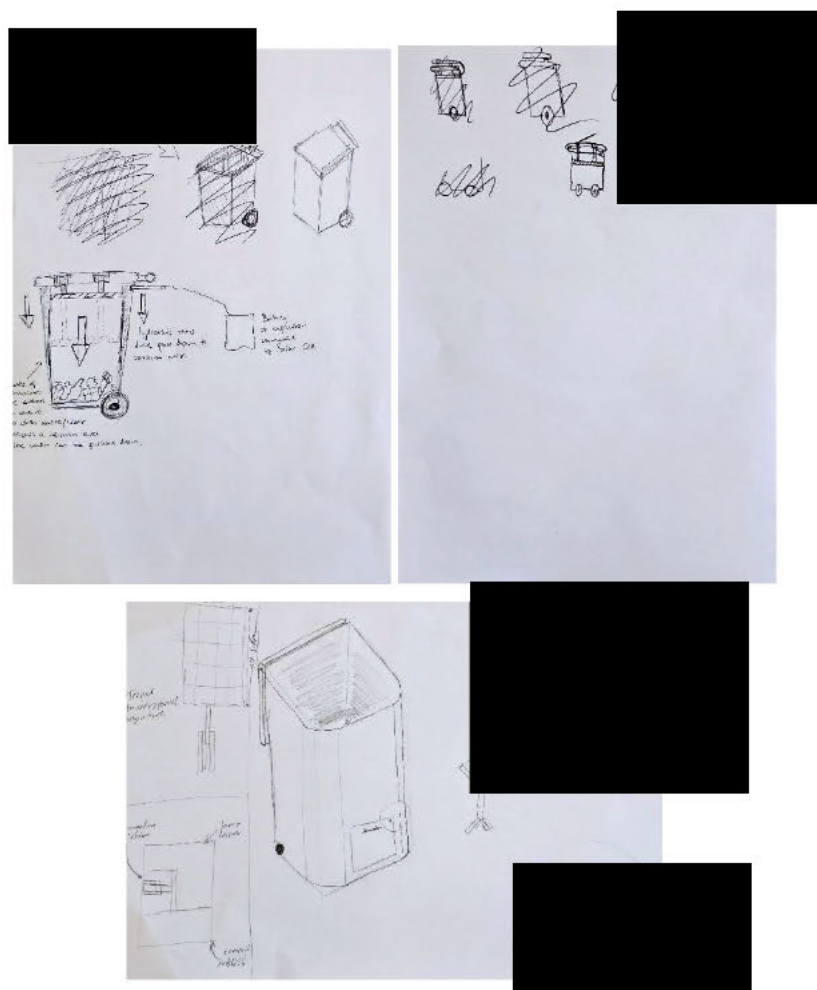


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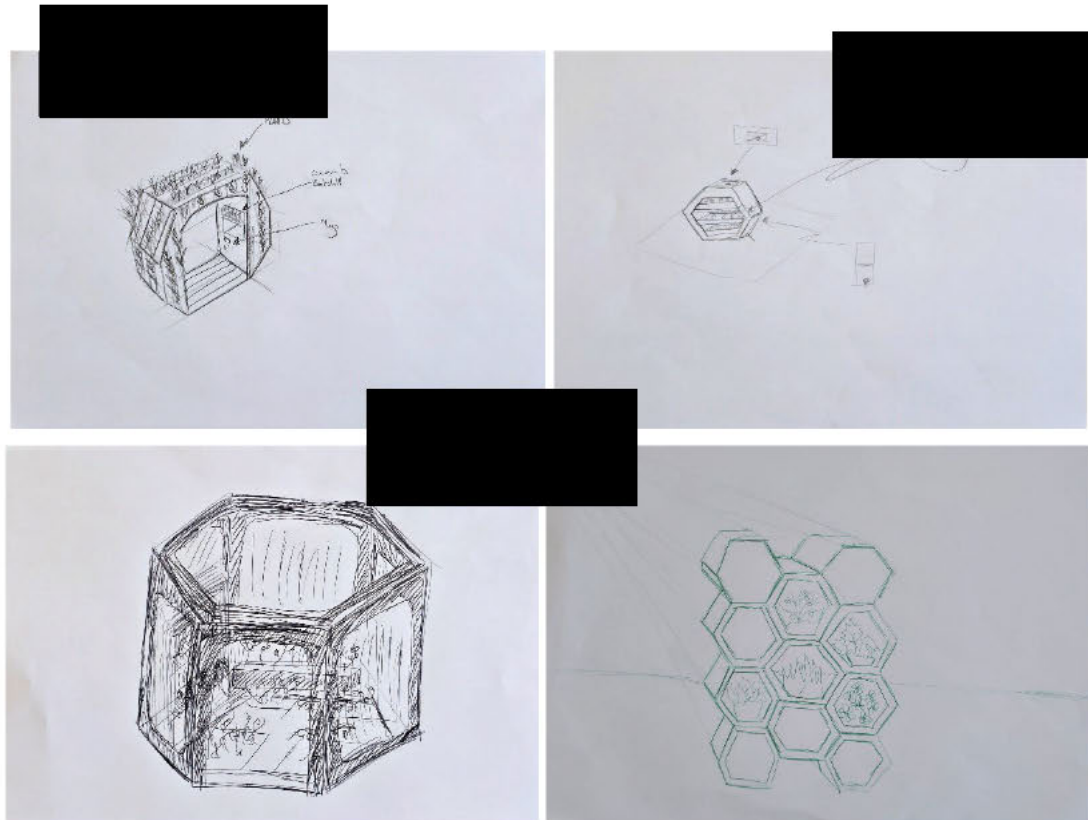


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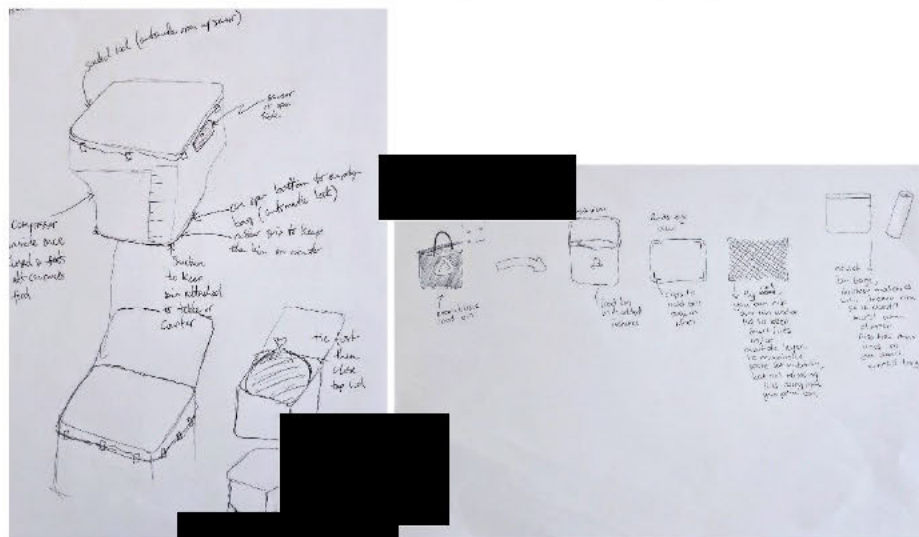
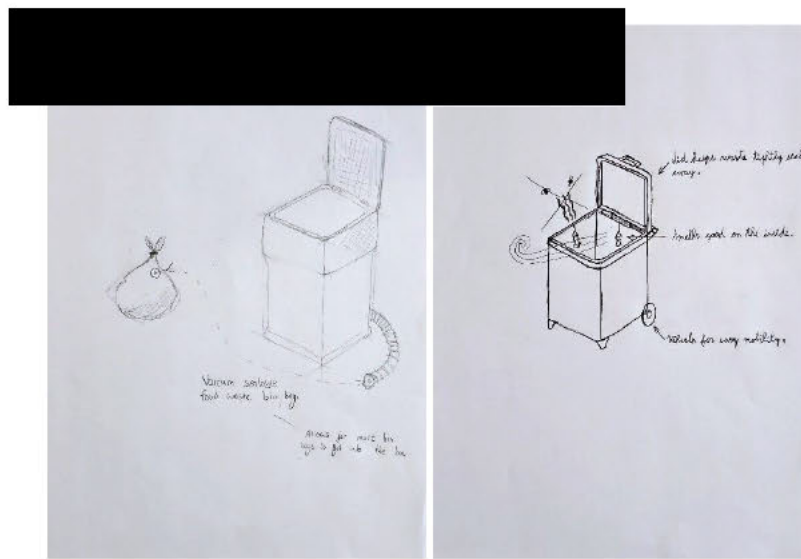




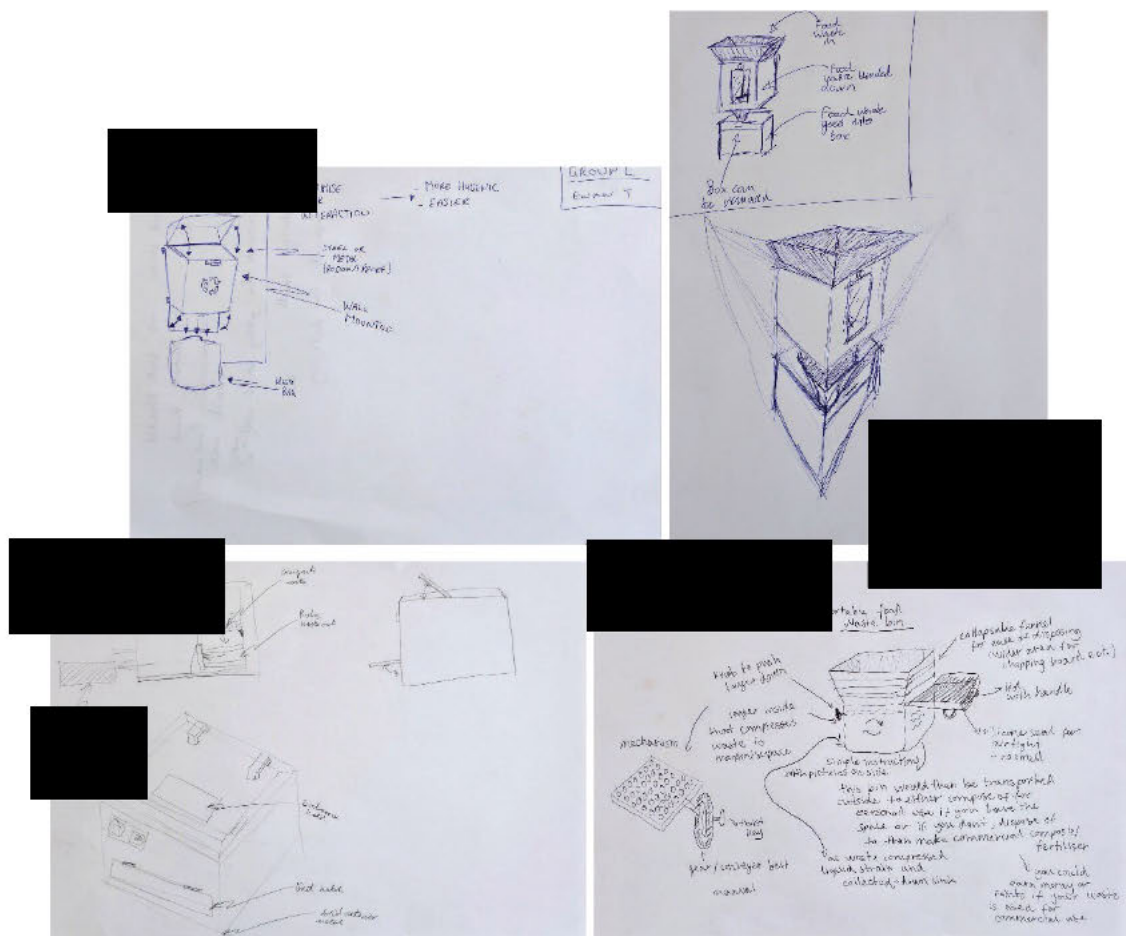
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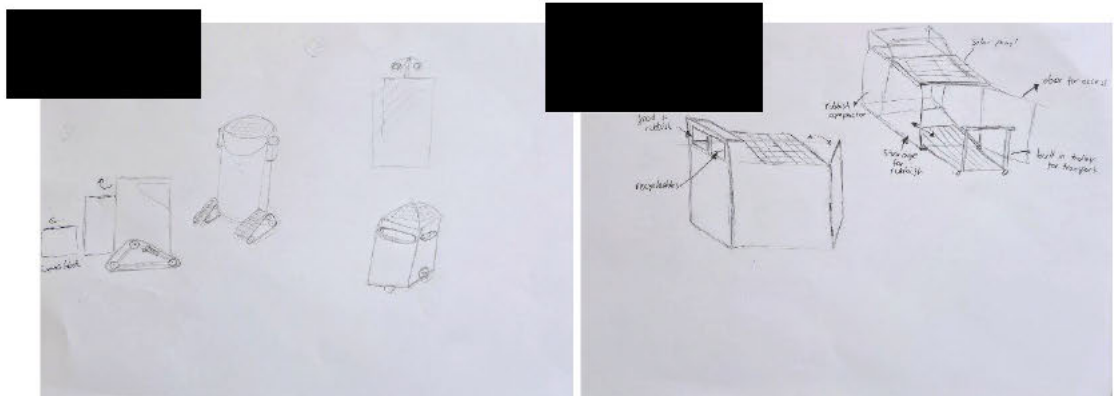
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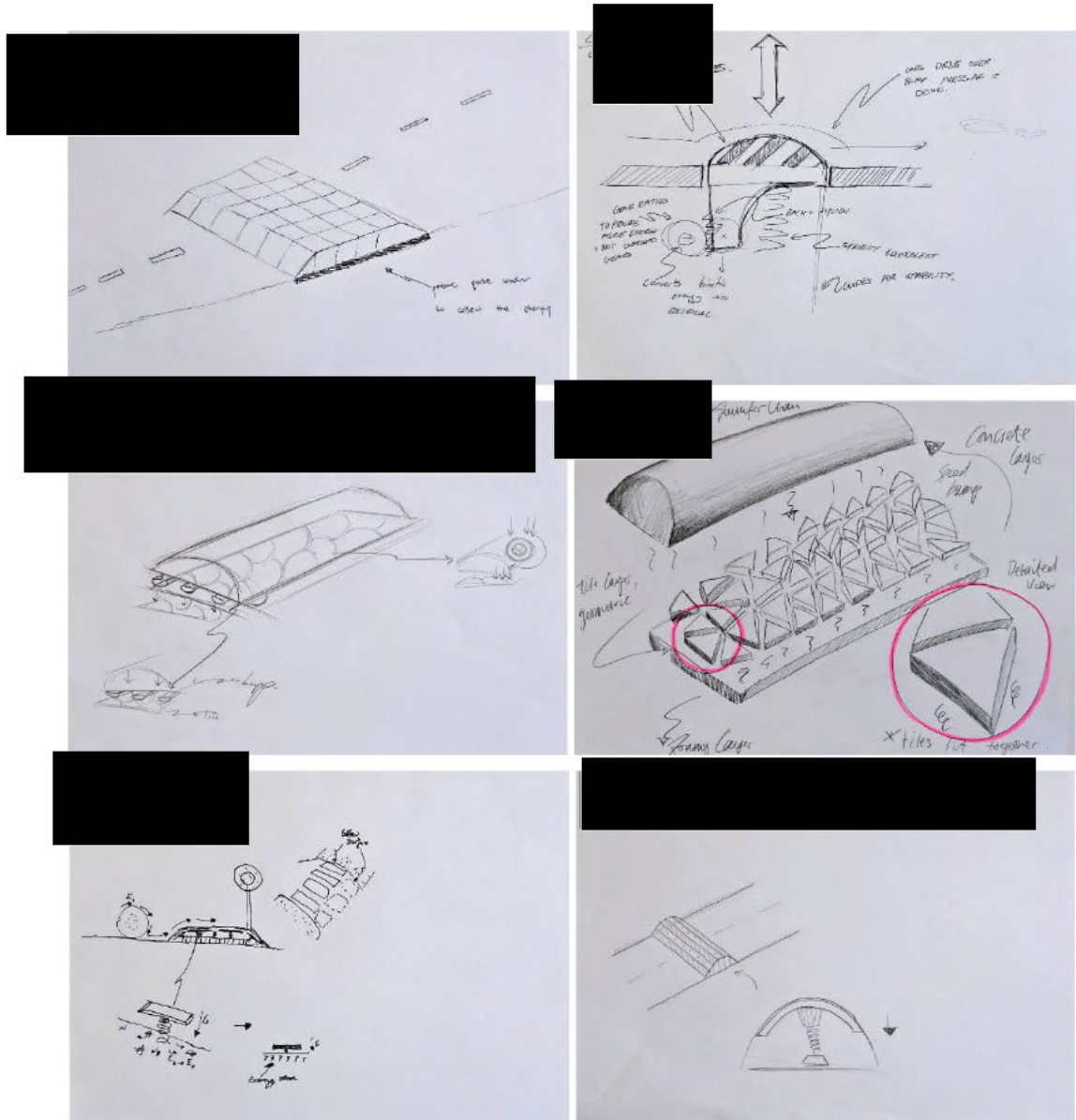
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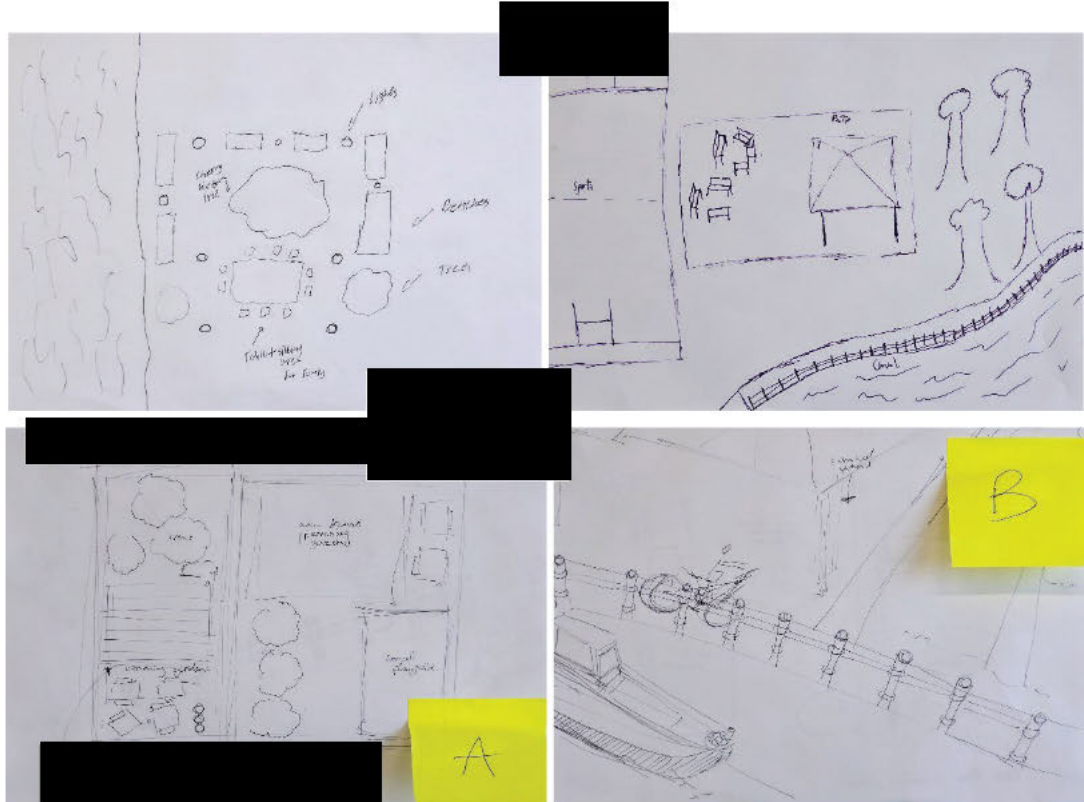
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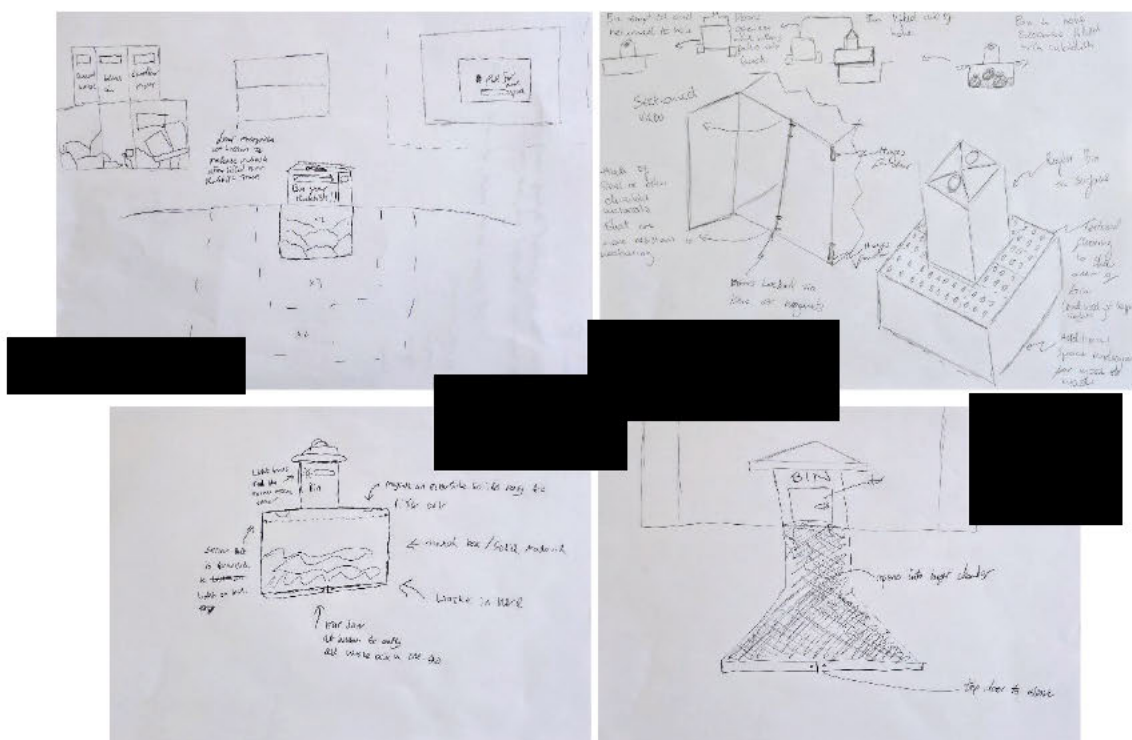
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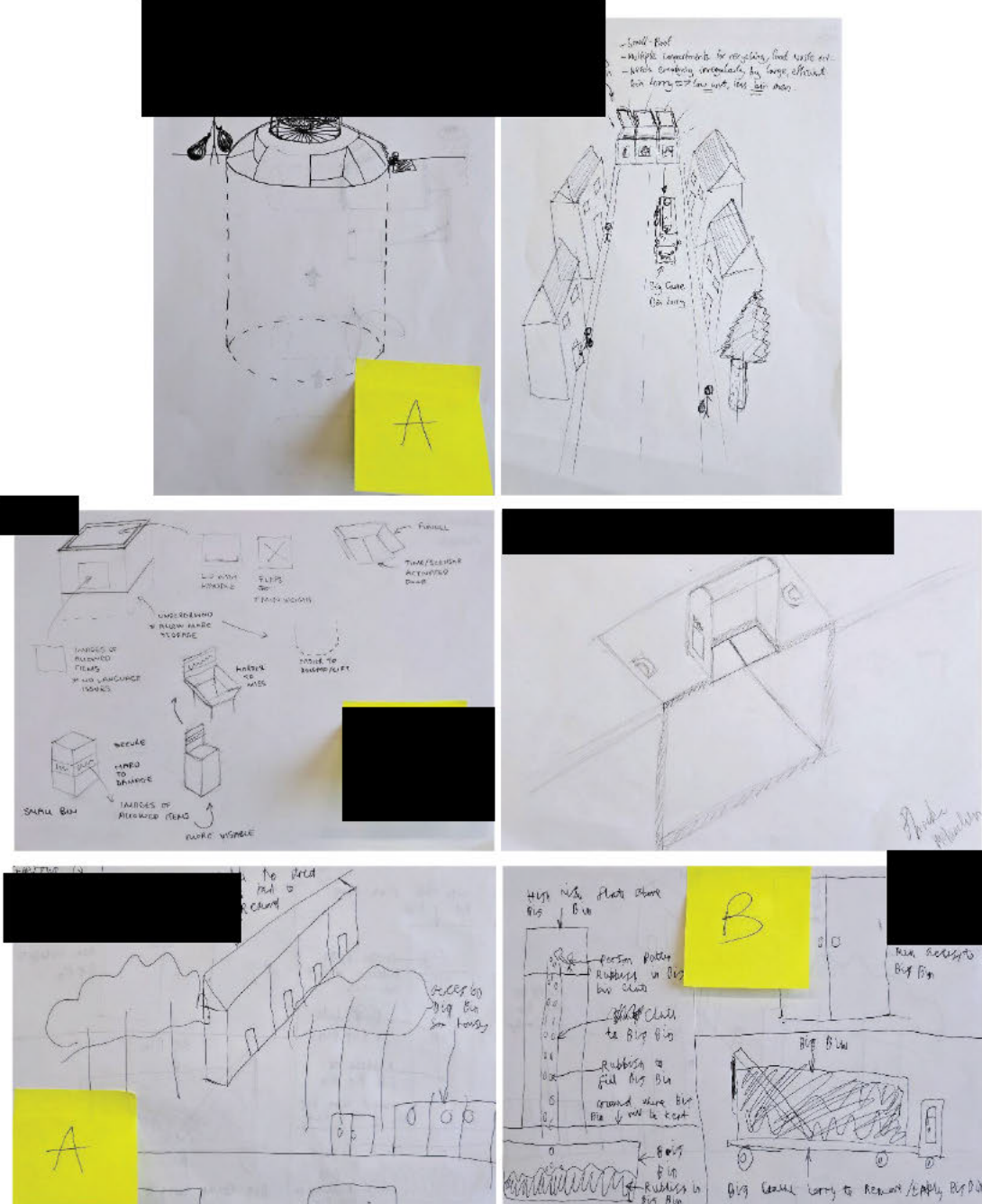
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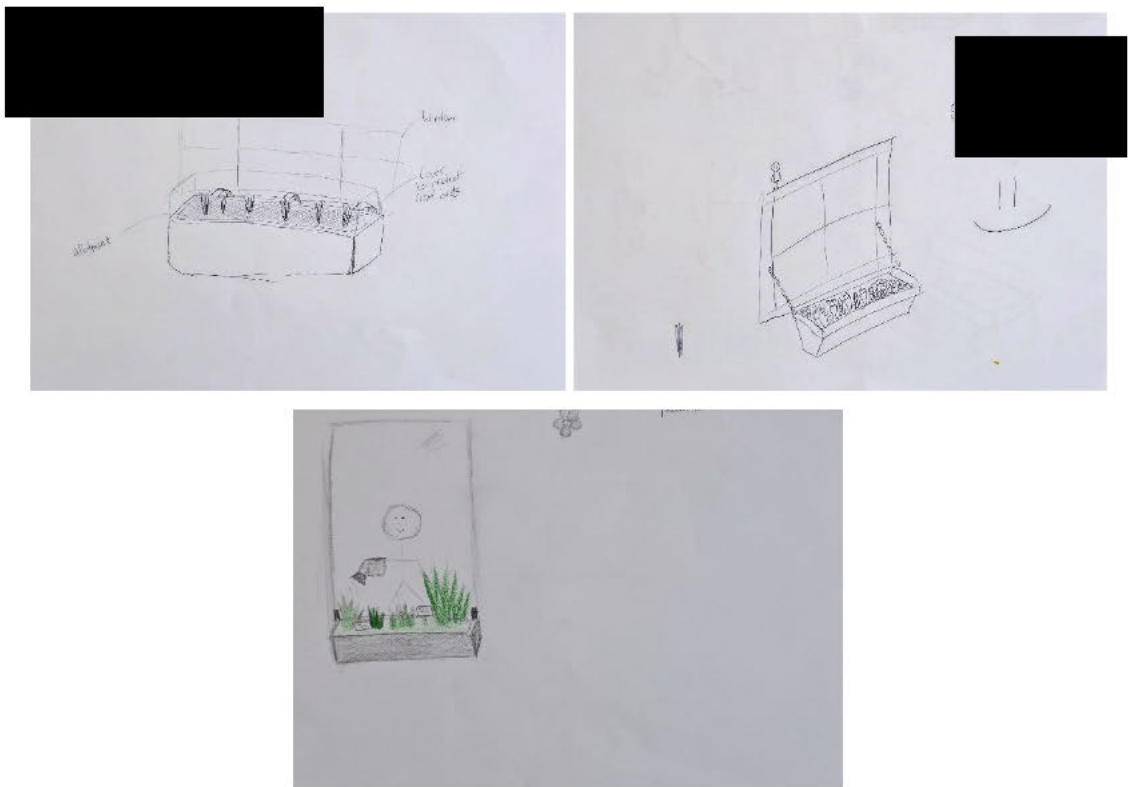
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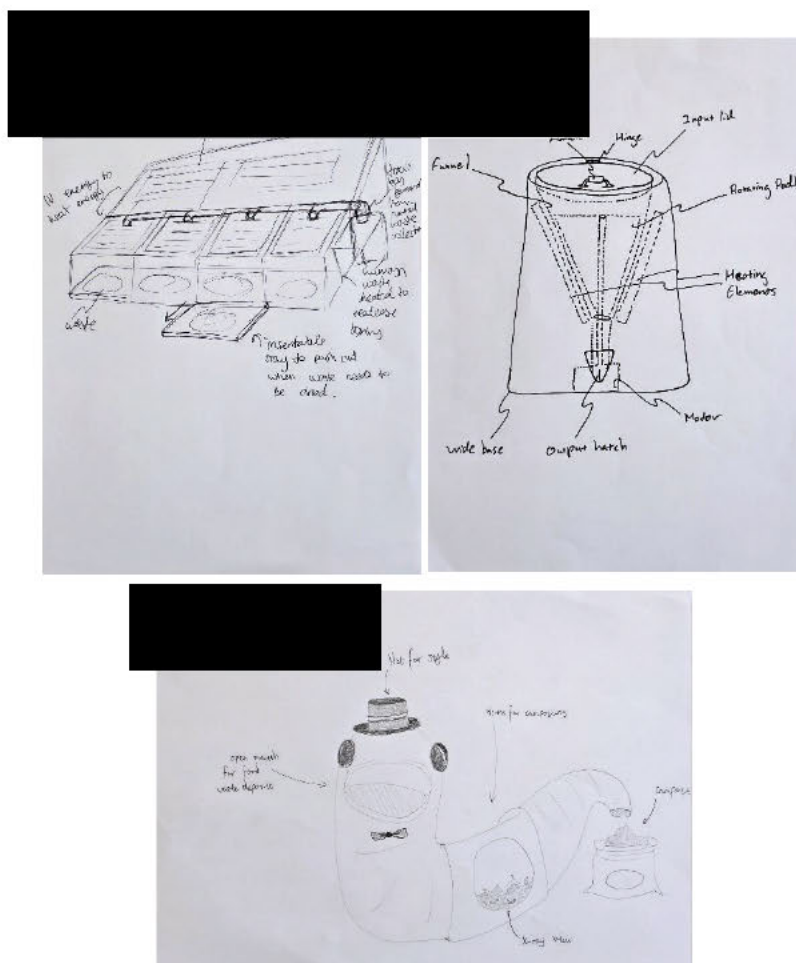
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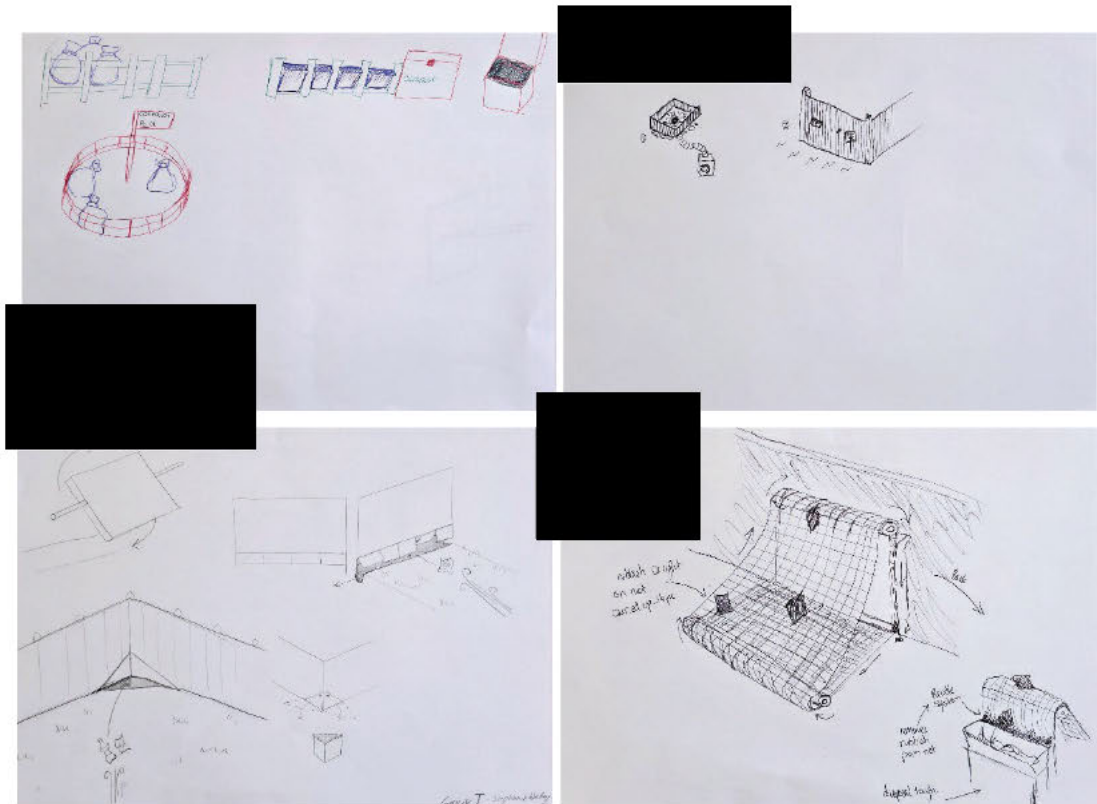
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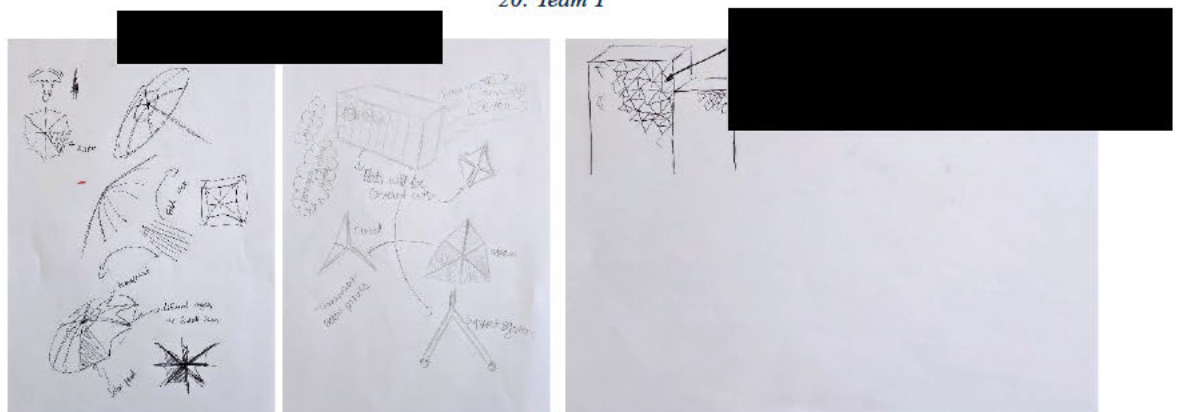
18: Team R



19: Team S

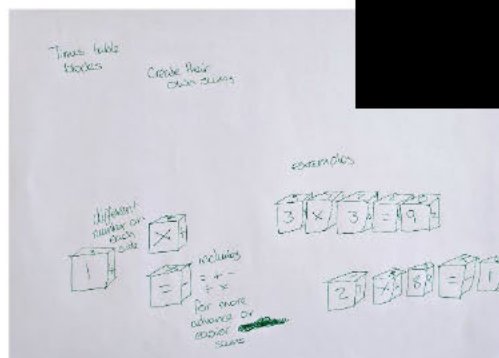
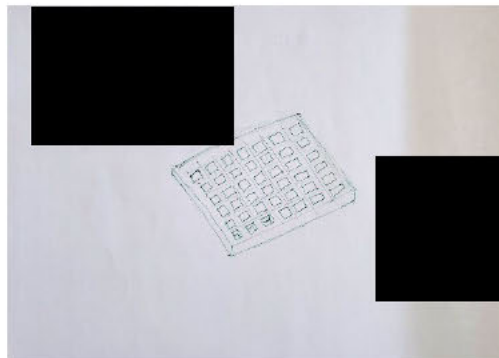
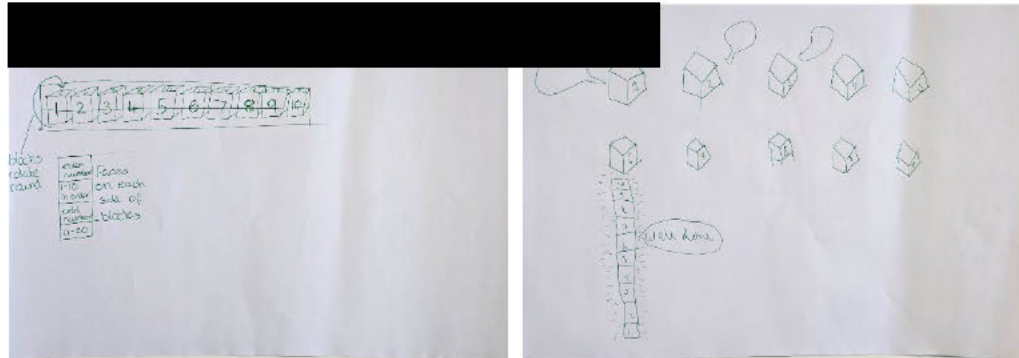


20: Team T

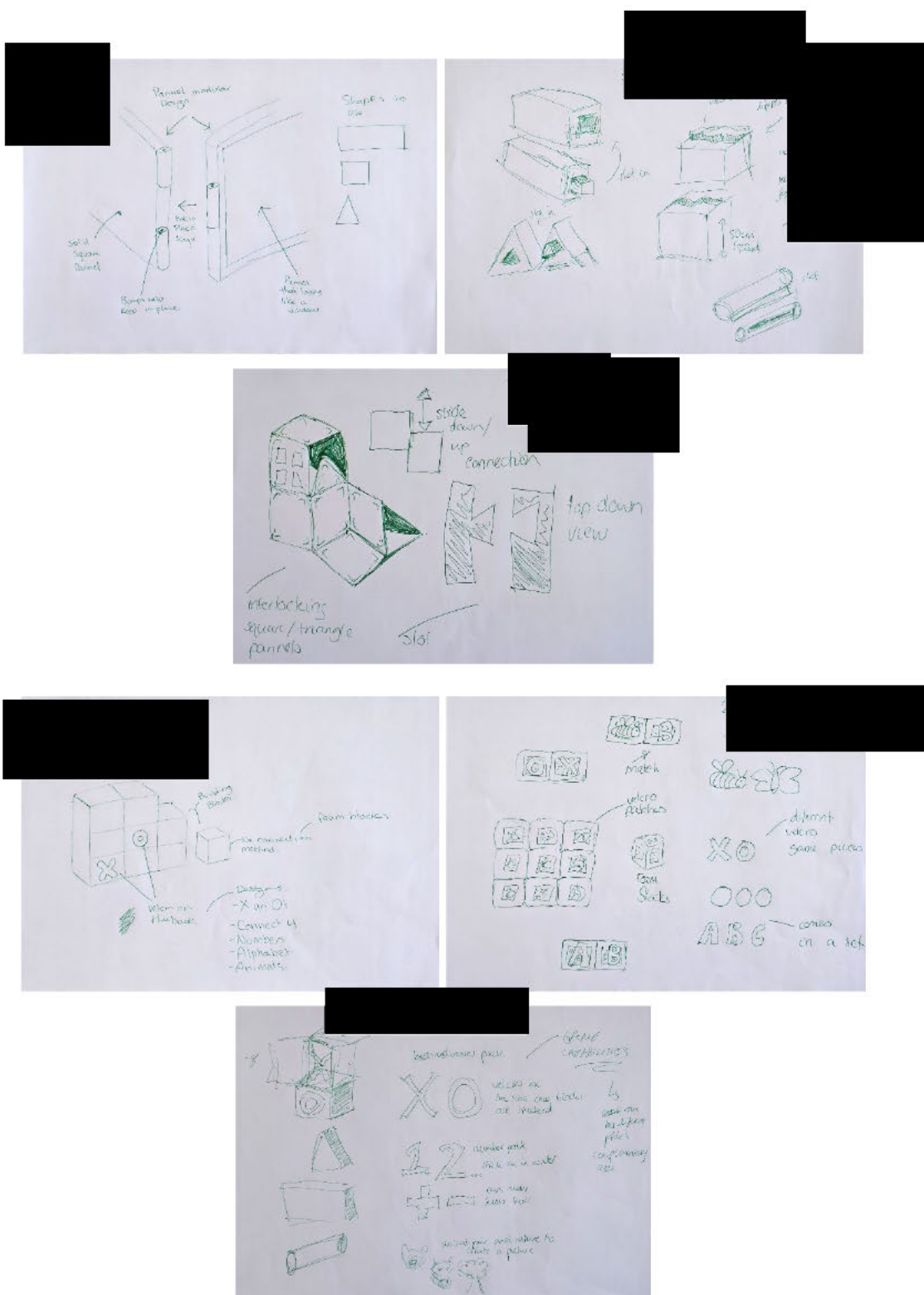


21: Team U

Appendix 32: DM411 SoYH sketches

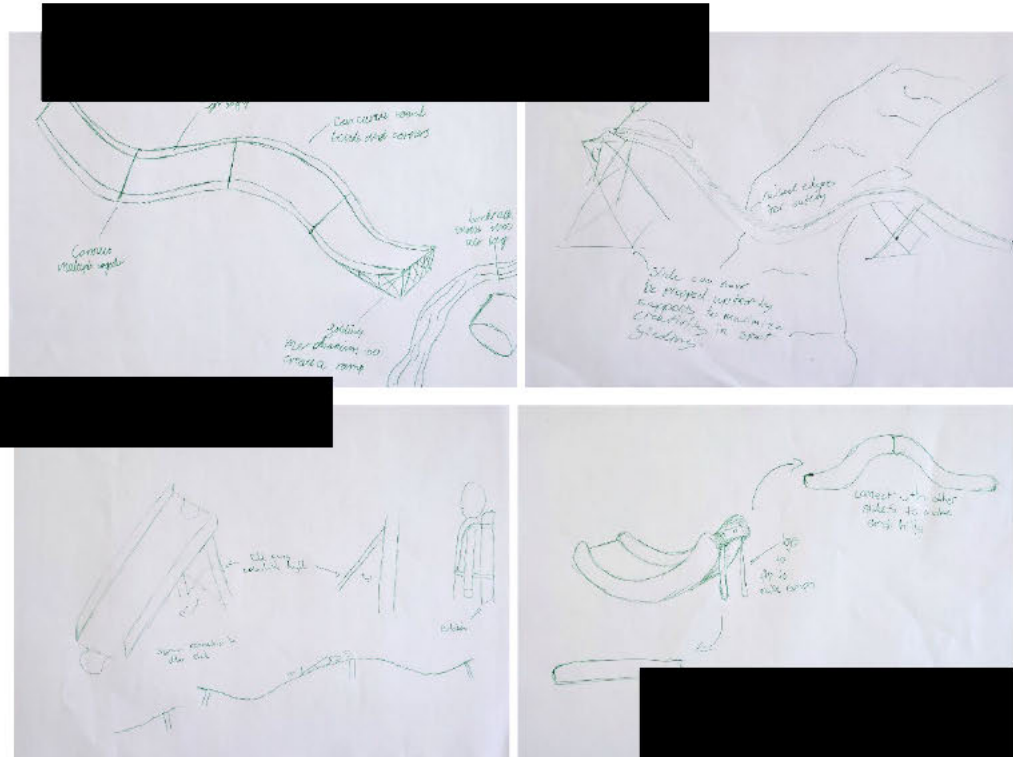




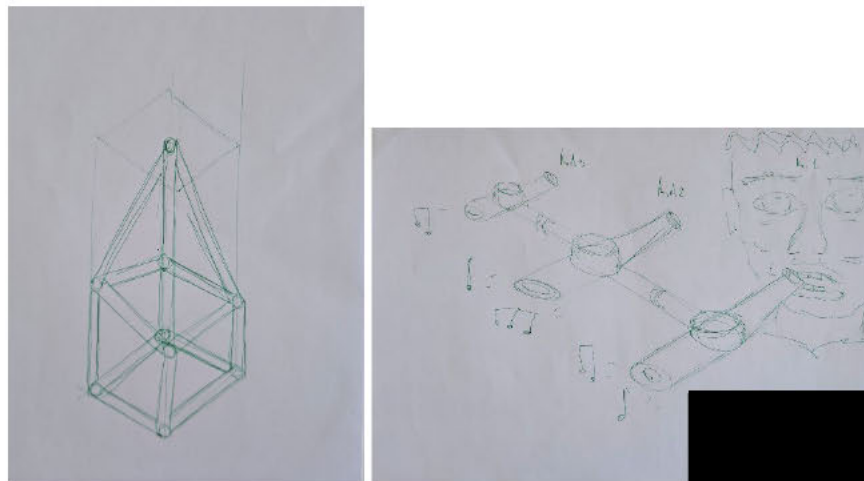


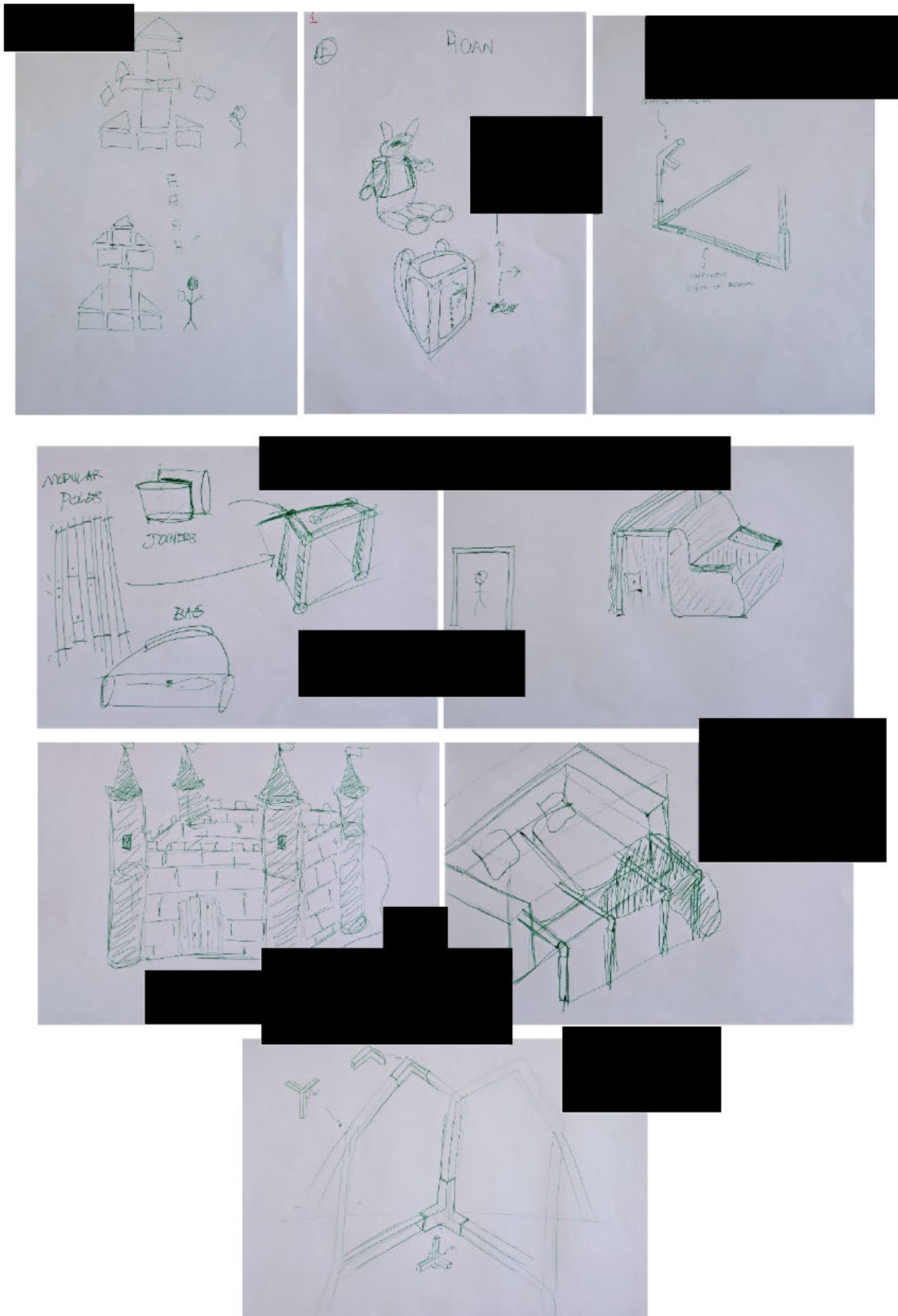
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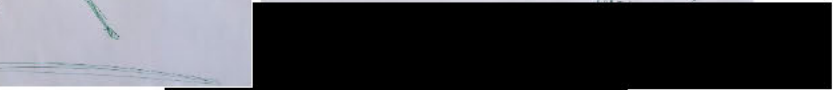




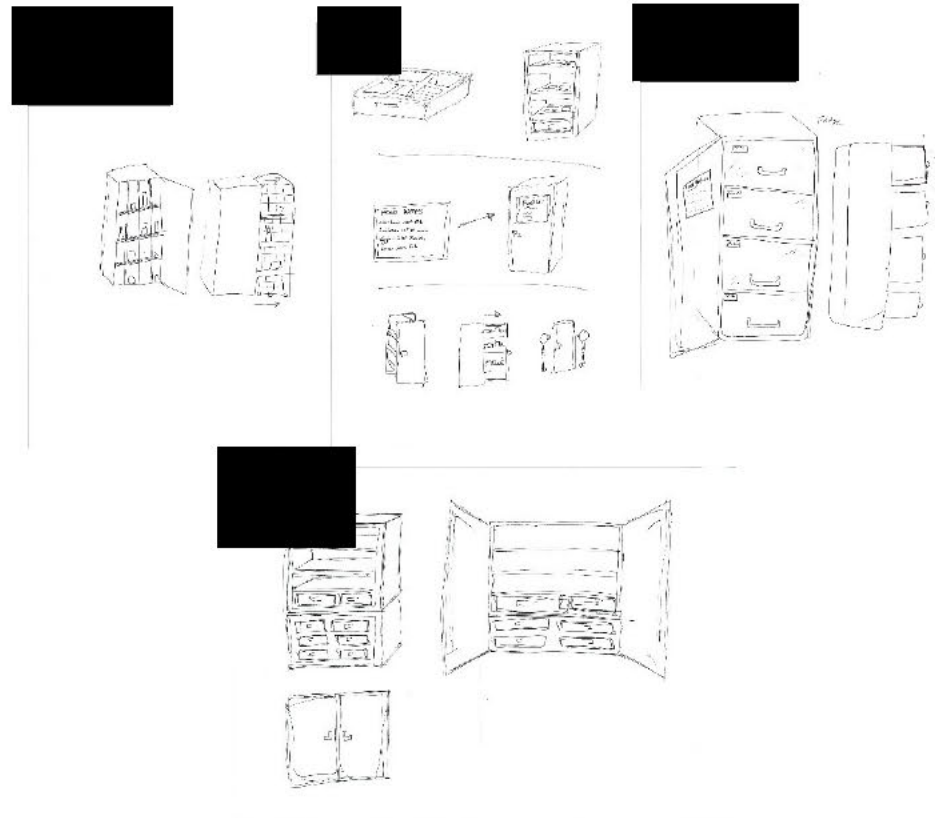
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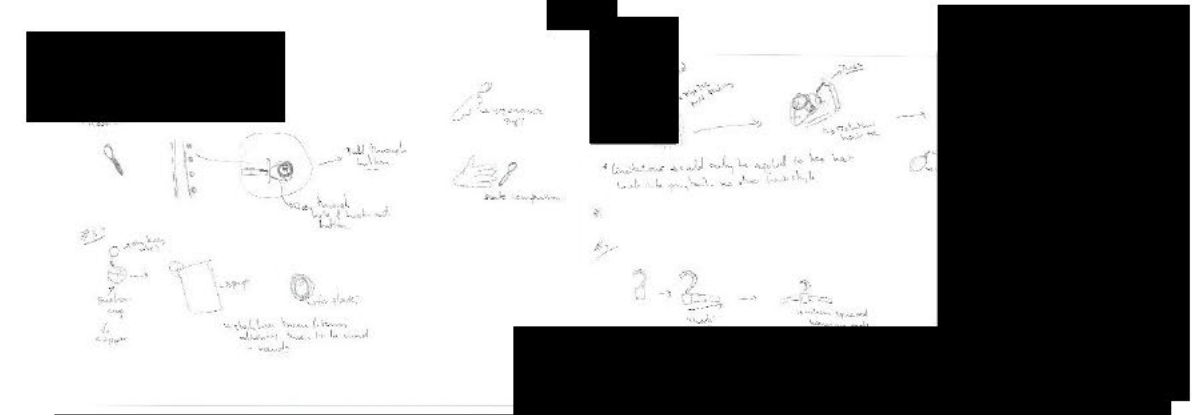


[illegible]

Appendix 33: DM306 SoYH sketches

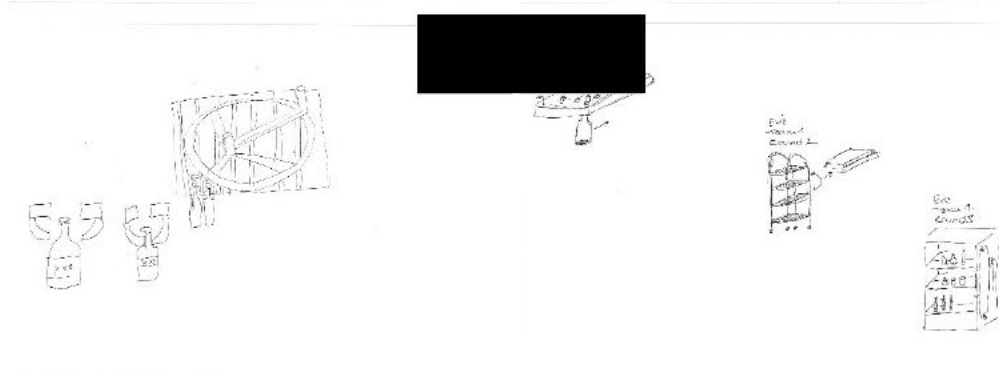
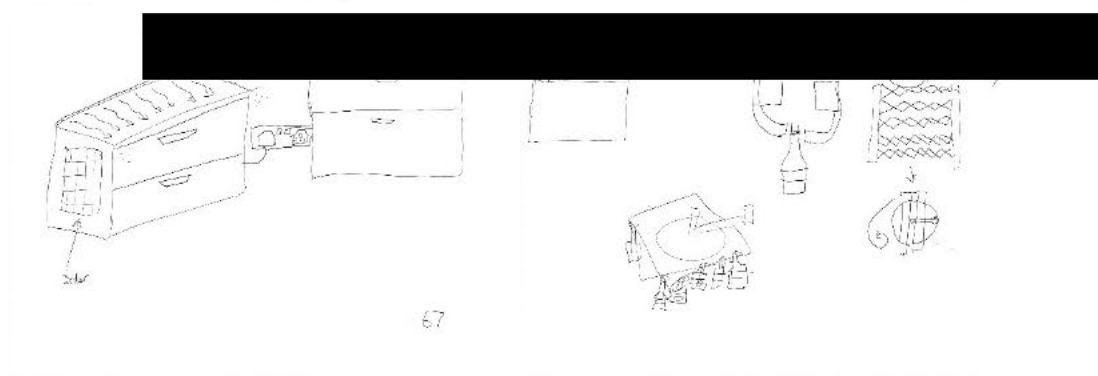
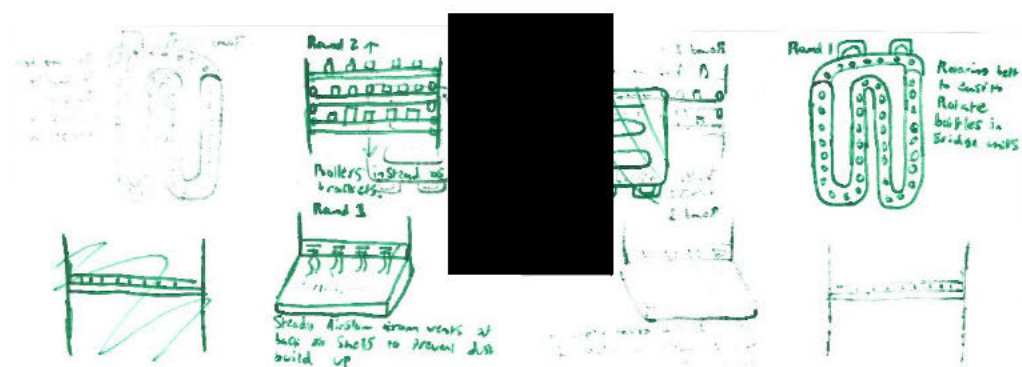


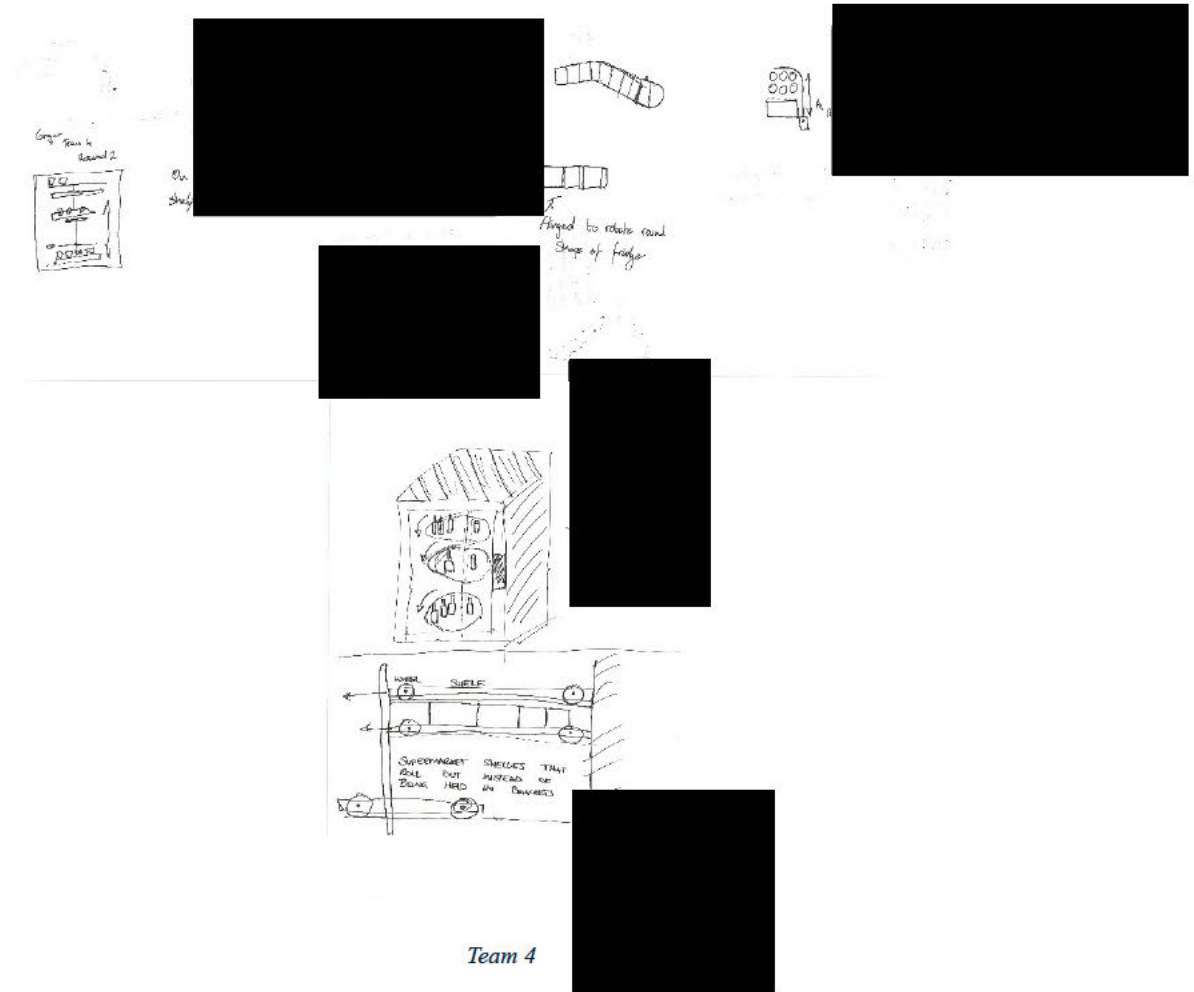
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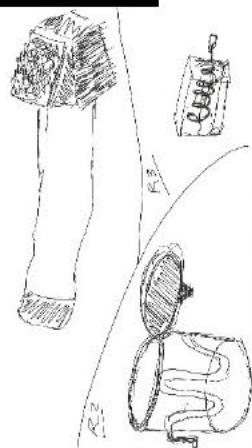
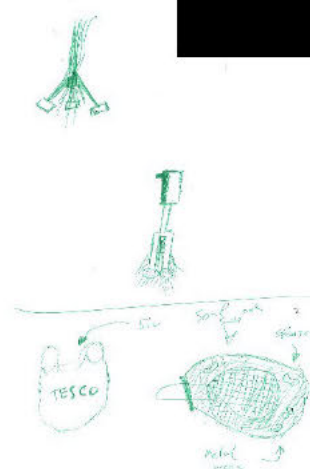
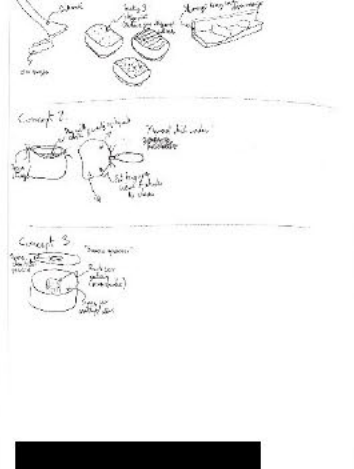
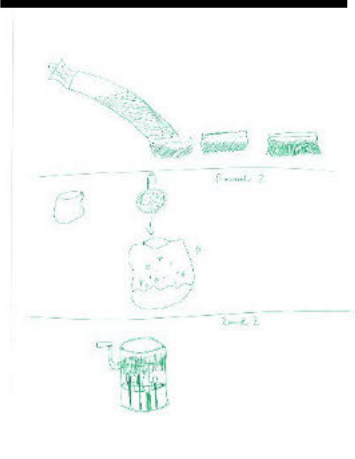
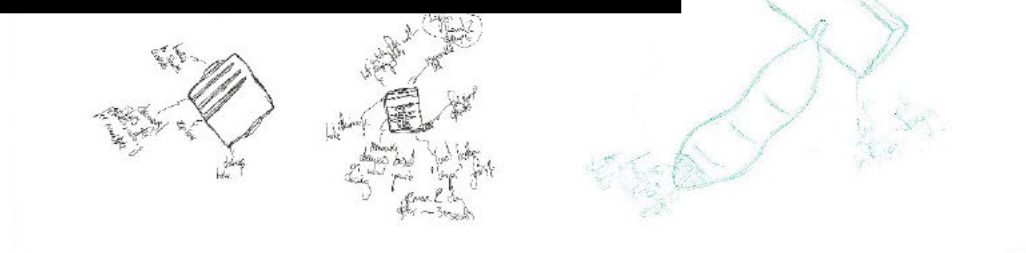
Team 3



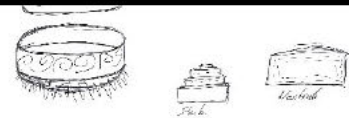
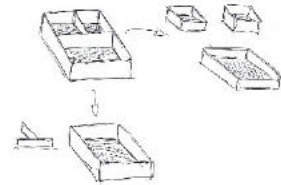
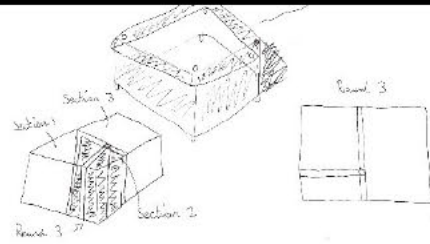




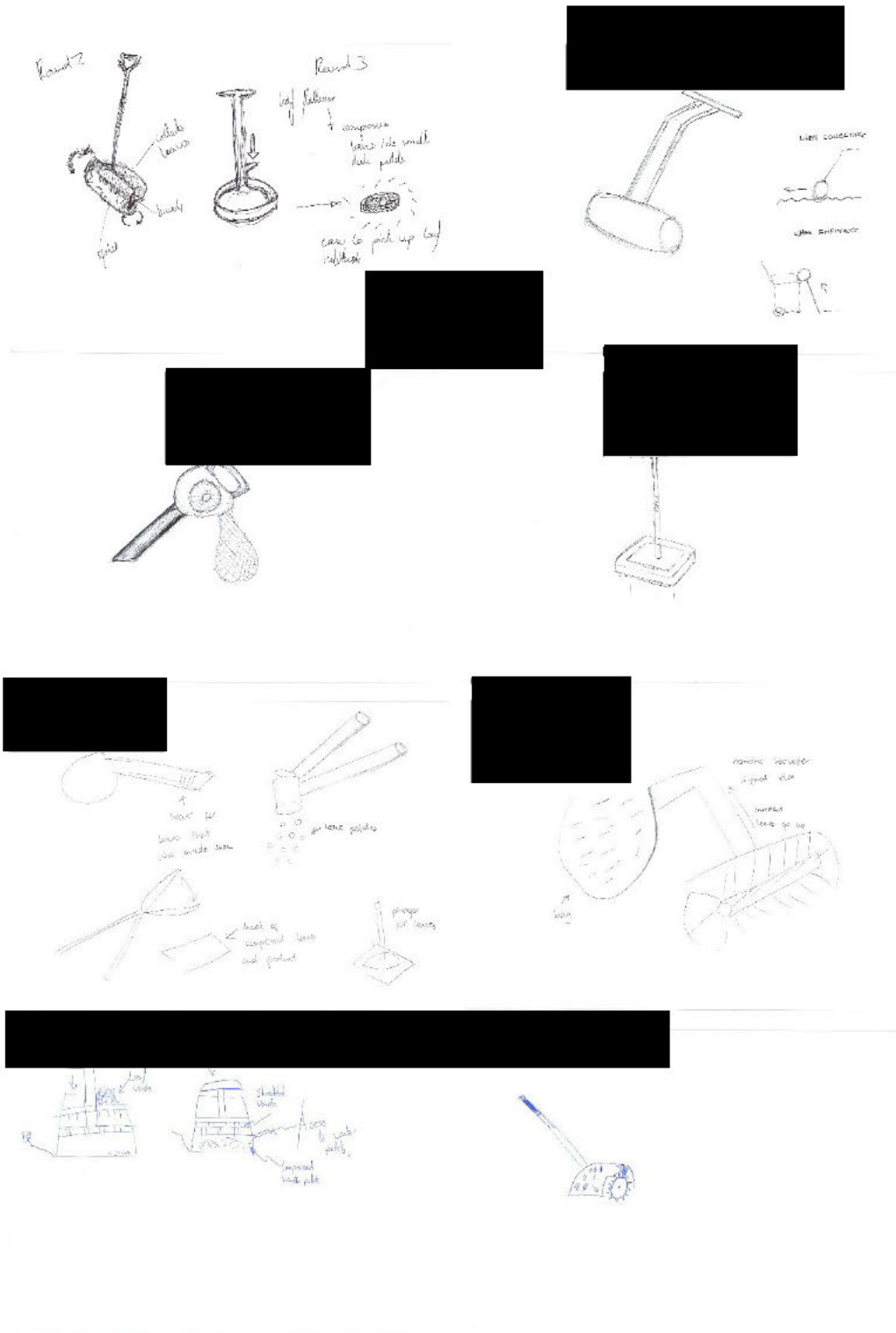
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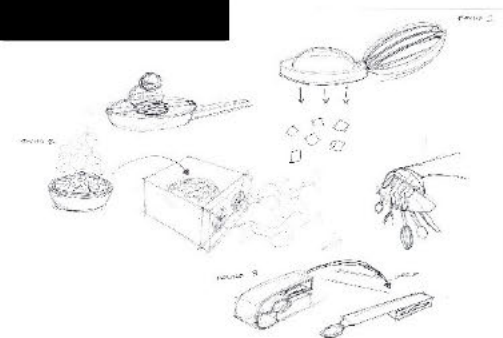
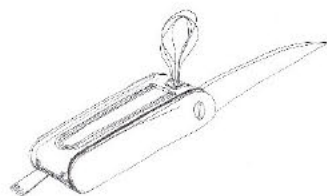
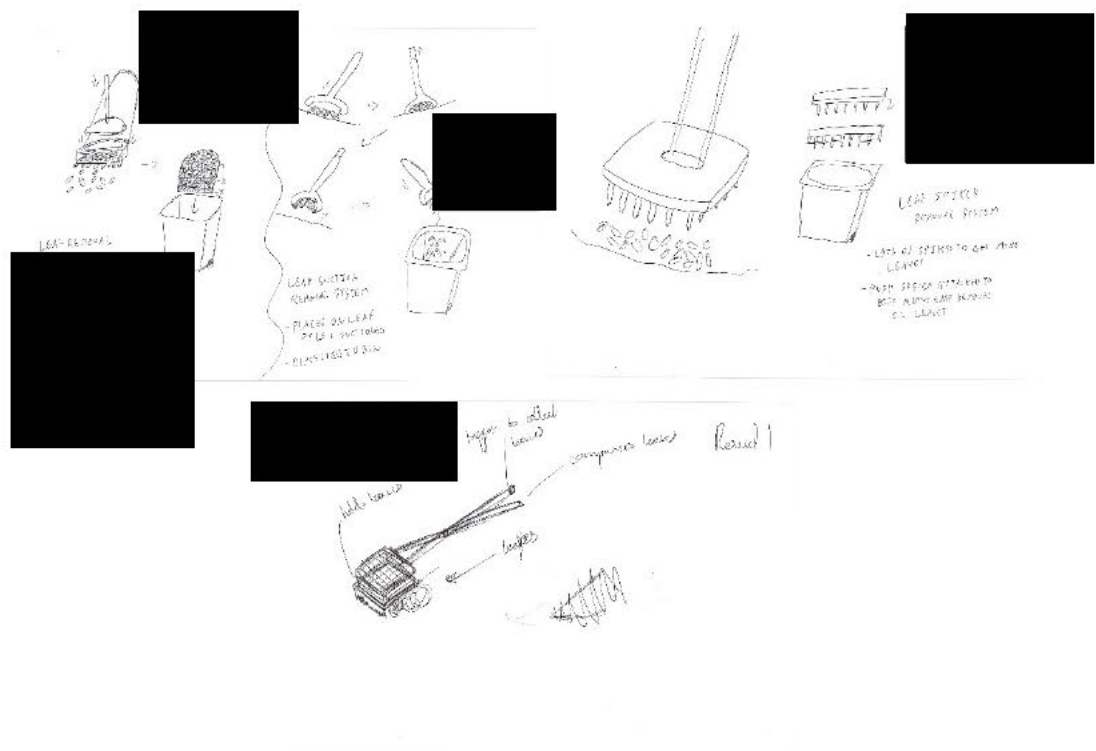


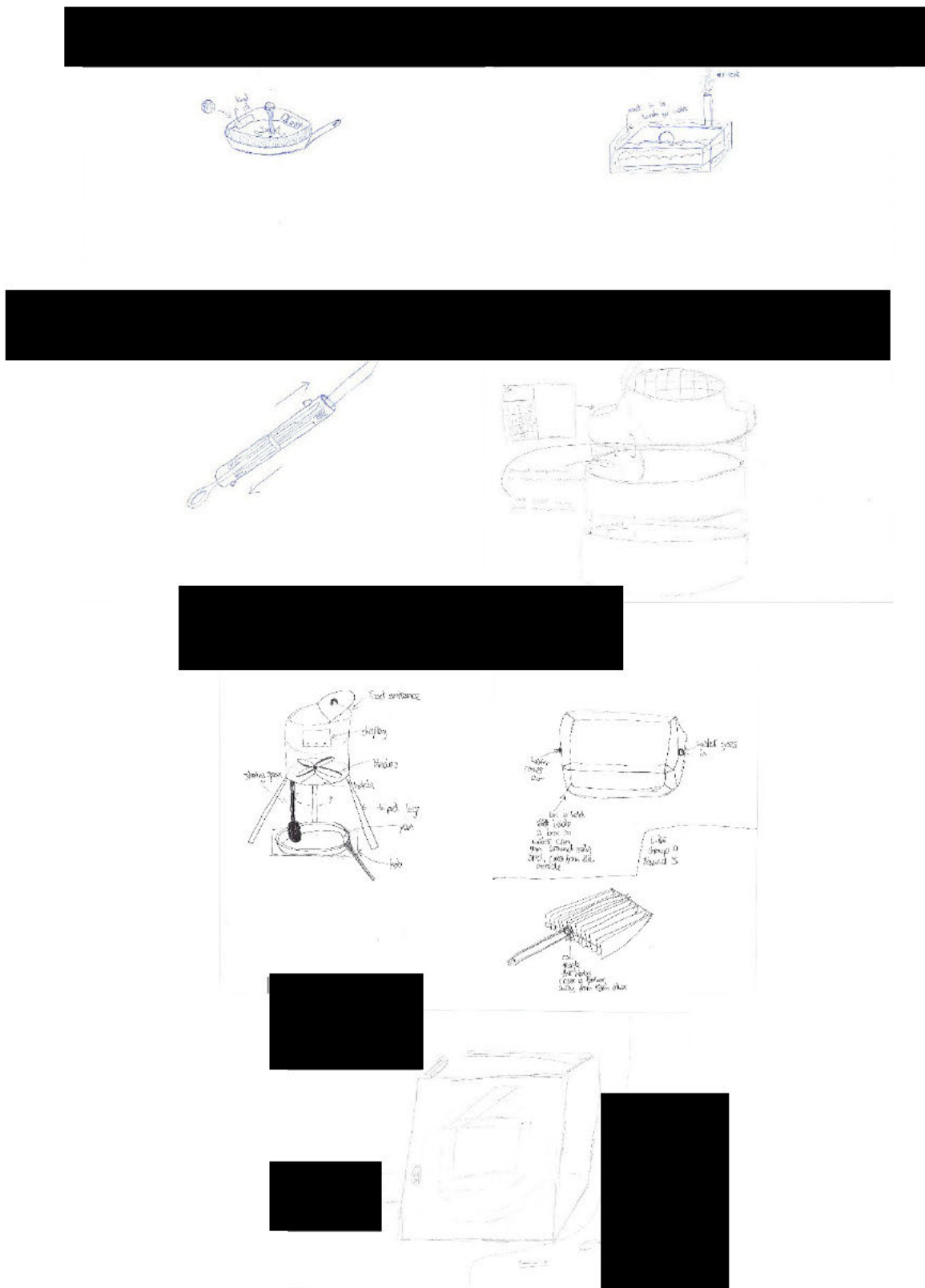
436



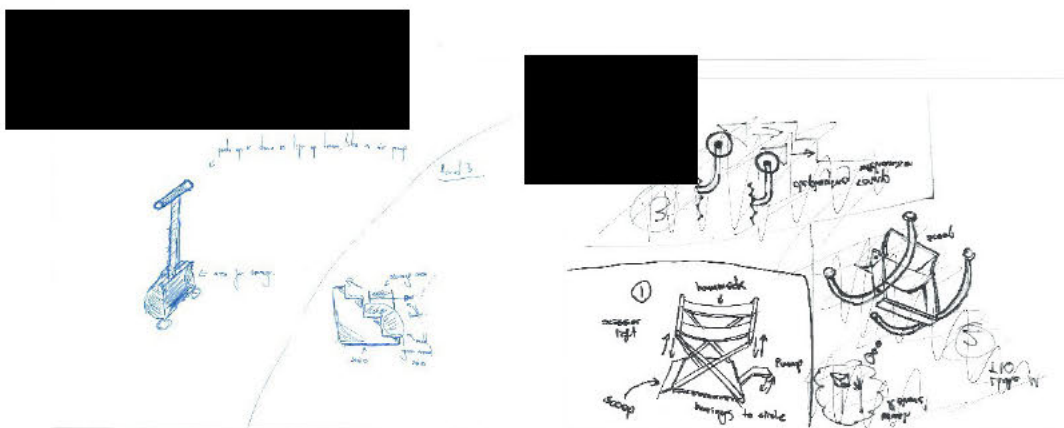
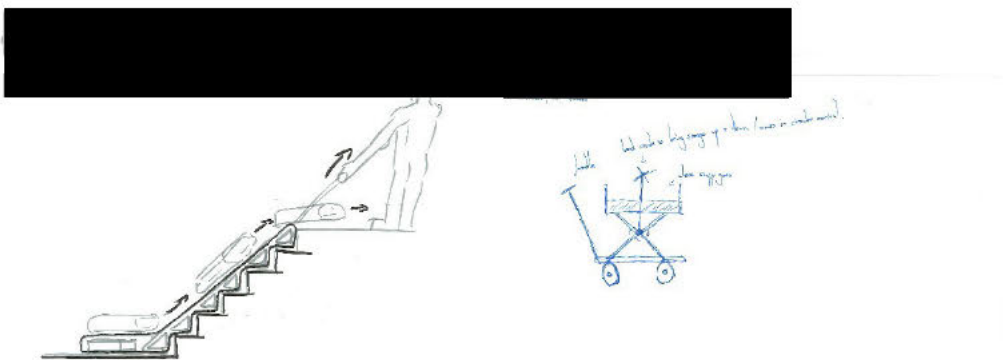
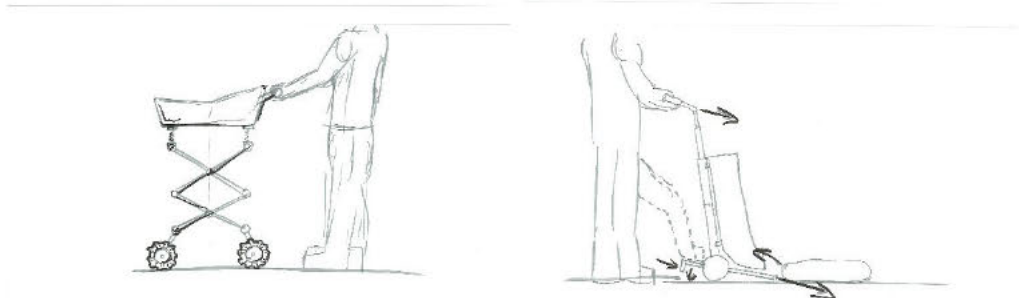
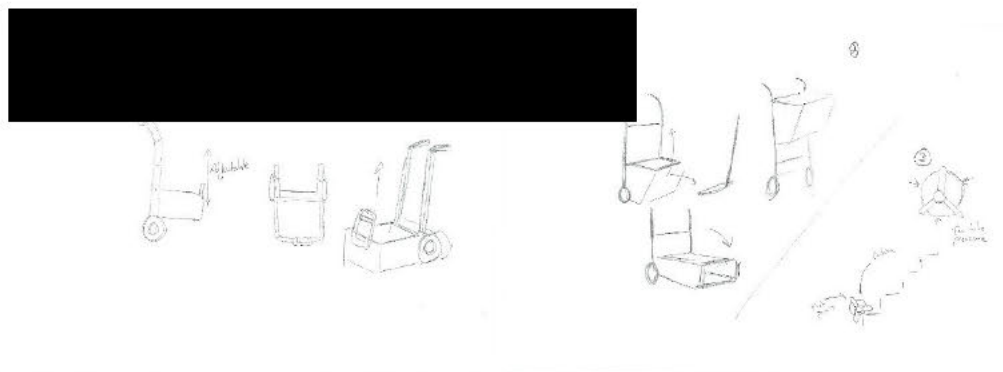
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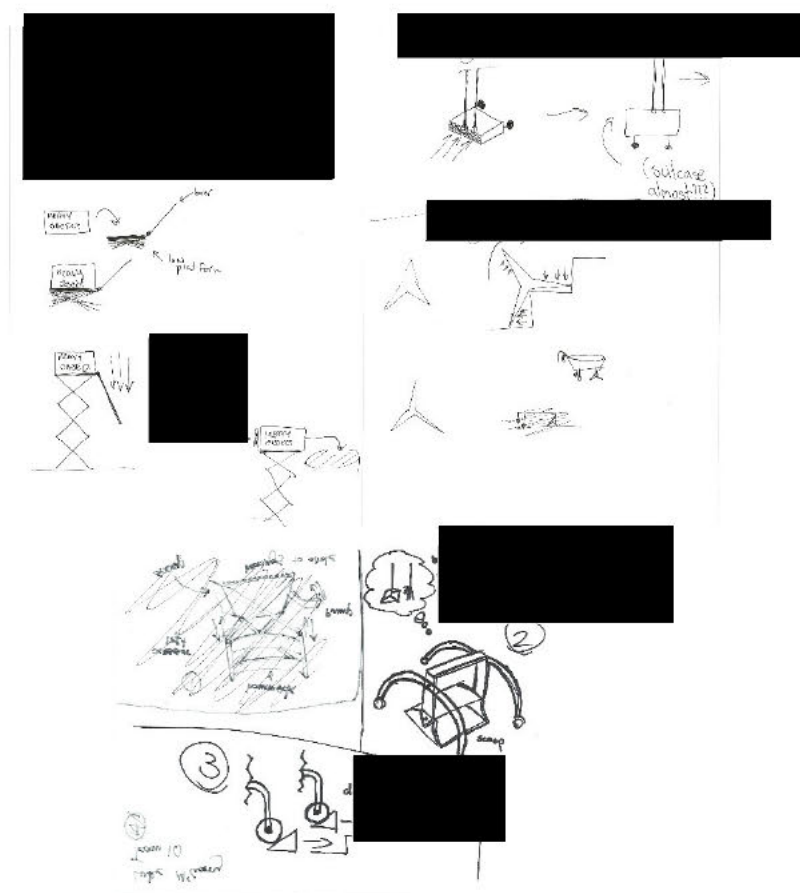




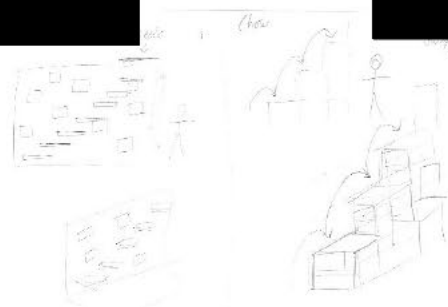
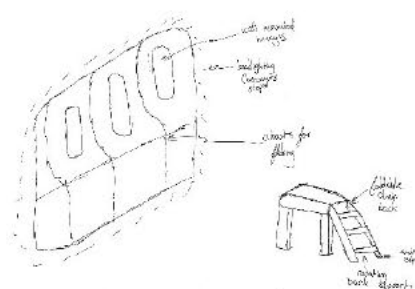
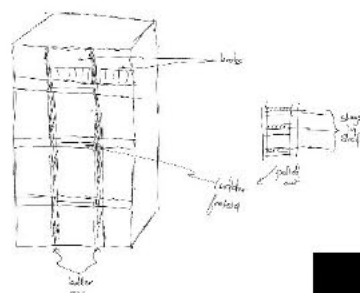
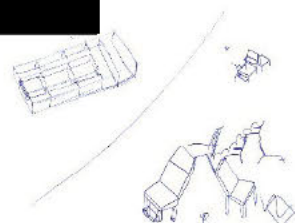
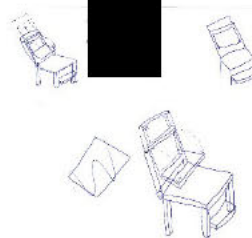
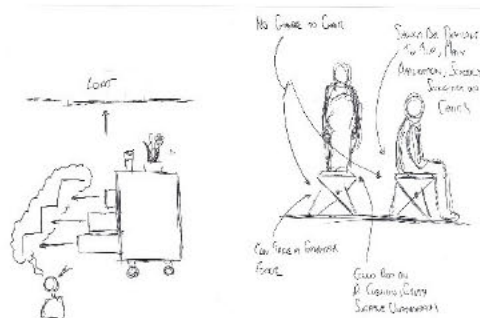
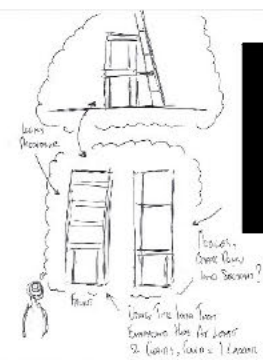
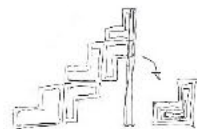
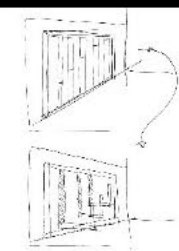


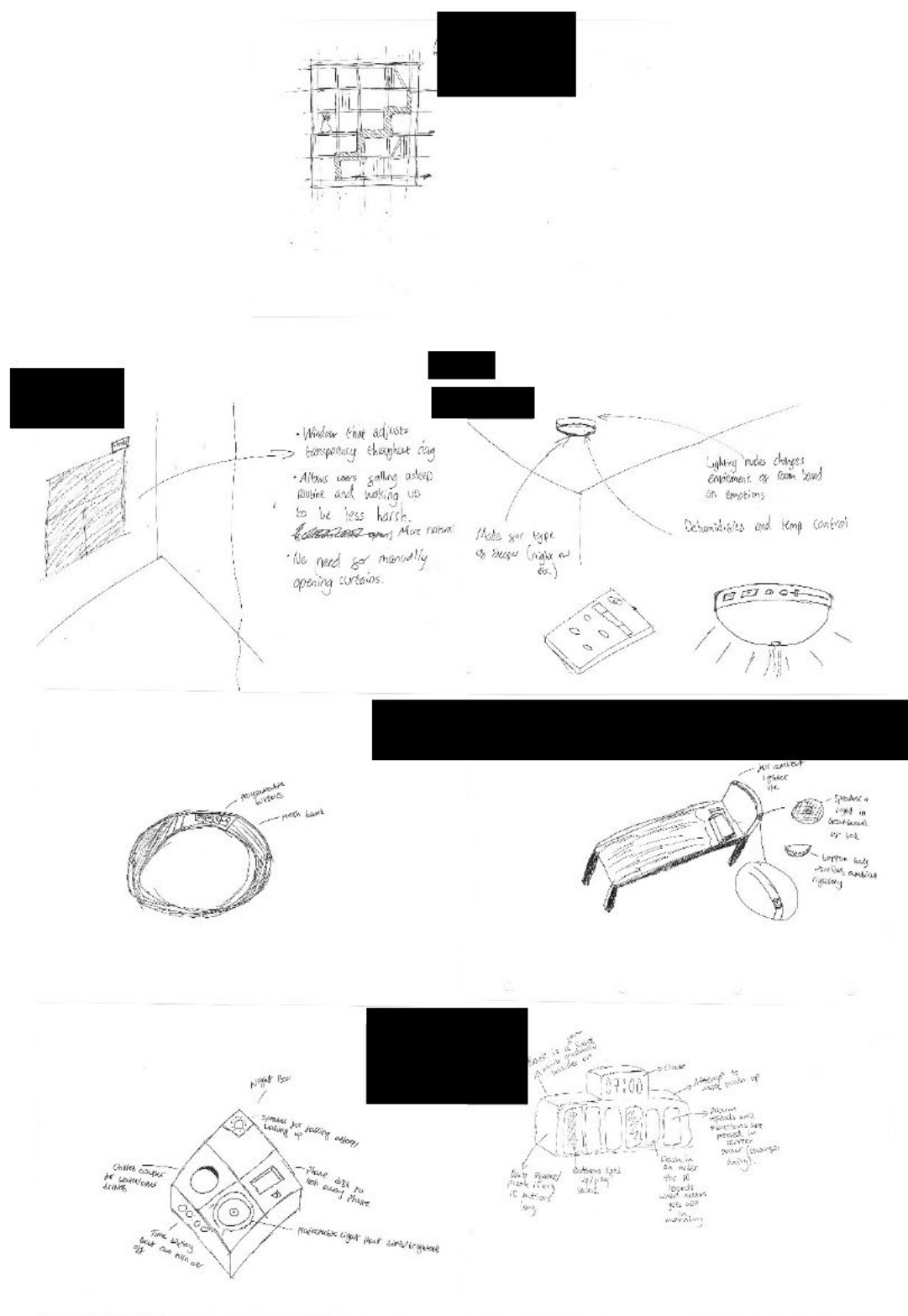
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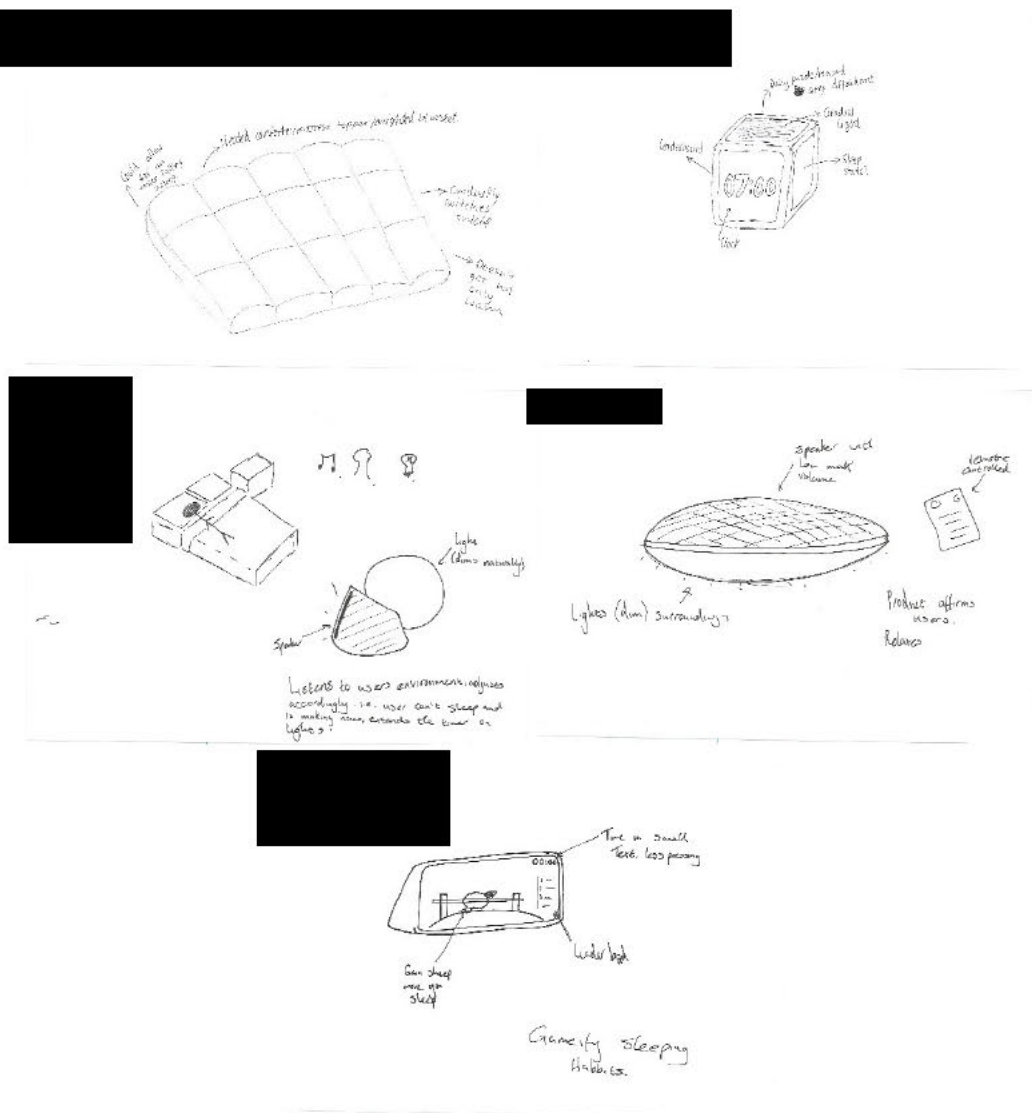




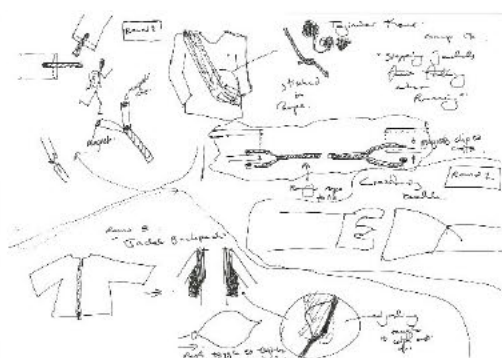
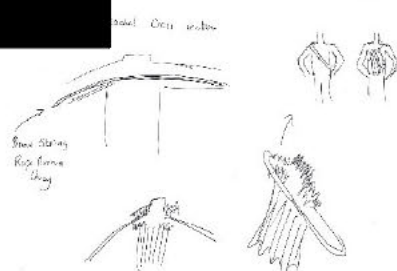
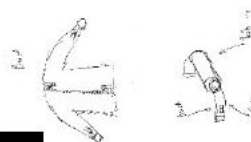
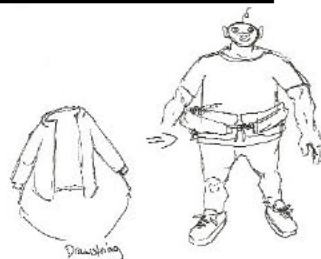
Team 10







Team 12



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Appendix 34: E&PDE 2026 abstract submission

Abstract of Contribution 179

A⁺ A⁺ A⁺ ?

Abstracts - Submission of

Topics: Challenges and opportunities for educators to foster an inclusive learning environment for students with diverse needs, Fostering EDI through engineering design educational methods

Keywords: Mental imagery, design cognition, engineering design, education, inclusivity

Mental Imagery Vividness and its Impact on Learning Attainment in Design Education

Rebecca Macfie, Ross Brisco

University of Strathclyde, United Kingdom

Mental imagery, the experience of perceiving an image within one's mind, has long been assumed to be an integral part of a designer's cognition. Recent research, however, has determined that this is not the case for every designer, and the experience of mental imagery in design differs between individuals. Designers, including those within engineering design, can experience mental imagery in varying levels of vividness across all sense modalities, from visual to emotional, and little is known about how these cognitive differences impact on their design process, or on their educational success. This paper poses the hypothesis: Does higher mental imagery vividness lead to better performance in a design class? By recruiting students from two engineering design classes to complete a psychometric questionnaire measuring multisensory imagery vividness and comparing these responses to final class grades, correlations have been determined between success in a design class and multisensory mental imagery vividness. The findings of this study confirm that the hypothesis posed is incorrect, with any correlations found showing that the higher a student scores their imagery vividness, the worse their final class grade is. These results pose further questions about the need for consideration of cognitive differences in design education and how we can create more inclusive learning environments in engineering design.

New, relevant work

Little has been researched on the impact of cognitive differences in terms of mental imagery experience in engineering design and design education. This work shows correlations between educational success in a design class and reported mental imagery vividness of design students that may allow for more inclusive learning environments to be developed which consider the cognitive needs of students.