Industry 4.0 and Augmenting the Millennial Worker

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This thesis is dedicated to my family,

for all their love, support, and emergency ice cream.

Declaration

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

Signed: ____

Date: ____

Previously Published Work

Excerpts of this thesis have been published in the following conference manuscripts and academic publications:

1. SMITH, E., SEMPLE, G., EVANS, D., MCRAE, K. & BLACKWELL, P. Augmented instructions: analysis of performance and efficiency of assembly tasks. International Conference on Human-Computer Interaction, 2020. Springer, 166-177.
2. SMITH, E., MCRAE, K., SEMPLE, G., WELSH, H., EVANS, D. & BLACKWELL, P. 2021. Enhancing Vocational Training in the Post-COVID Era through Mobile Mixed Reality. Sustainability, 13, 6144.

Abstract

Across the engineering industry, accuracy and time taken to complete work items are priorities in manufacturing and maintenance work. On-the-job training can be time-consuming and have serious consequences if done improperly, resulting in waste, lost production, and equipment downtime. This is particularly true in the offshore wind industry where even accessing assets can take several hours, incurring high costs and leading to health and safety risks.

In recent years, the engineering industry has been transformed by the adoption of Industry 4.0 technologies. One such technology is Augmented Reality (AR). AR has been demonstrated to have some success as an instructional tool in the literature, but questions remain over the best way to present information. Therefore, this thesis presents a series of experiments to determine the most effective way of conveying AR instructions. Another way to utilise AR is to meet the engineering skills gap in training and education to prepare the workforce of the future. Consequently, two case studies show how AR has the potential to transform engineering education and training.

This information can be of value to anyone considering implementing an industrial AR system whether for training or instructional guidance, thus paving the way for a more widespread adoption of AR technologies in engineering and manufacturing and has potential to improve operational efficiency in the industry.

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Key Definitions and Acronyms

Acronym	Term	Meaning
	Box's M test	Parametric test to compare variation in multivariate data
	Cohen's D	Measure of effect size in experimental work
	COVID-19	Contagious disease caused by the SARS-CoV-2 virus, commonly referred to as the coronavirus
	Duplo	Construction toy aimed at very young children
	Digital Twin	A digital model of a physical asset, process, or system
	Effect size	Measure of the strength of a relationship between two variables in a sample
	Epistemology	The critical study of the nature of human knowledge
	Generation X	Demographic of people born between 1965 and 1980
	Generation Y	Demographic of people born between 1980s and 2000s
	Generation Z	Demographic of people born after 1995
	Interpretivism	Research philosophy based on the assumption that phenomena can only be fully understood through subjective interpretation
	Kurtosis	Measure of "tailed-ness" of a distribution
	Kruskal-Wallis non-parametric test	Method for testing whether samples share the same underlying distribution
	Lego	Construction toy
	Levene's test	Method of assessing quality of variance between two or more groups
	Localisation	Determination of an object's pose relative to a global reference frame
	Millennial	Alternative term for Generation Y
	Methods	Collection and analysis of data to develop new knowledge
	Methodology	General research strategy
	Ontology	The study of the nature of reality and being
	Positivism	Research philosophy based on the assumption that reality can be observed and measured objectively

	Pragmatism	Research philosophy with a focus on practical results, where researchers have freedom to choose whichever methods suit the problem best
	P-value	The probability of a result occurring without any differences in underlying populations
	Shapiro-Wilks test	Statistical test of normality in a sample
	Significance Level	Measure of the strength of evidence that must be present to conclude a significant difference
	Skewness	Measure of asymmetry of a distribution
	Statistical Power	The probability of detecting a result if that result truly exists
	Tracking	The measurement of an object's pose relative to the environment
	T-Test	Statistical method using inference to determine significant differences between group means
	Type I error	Incorrectly identifying a relationship between variables where none exists
	Welch's ANOVA	Variation of ANOVA which is not sensitive to violations of the assumption of equality variance
2D	2-Dimensional	Objects which can be measured in two directions (e.g., length and width)
3D	3-Dimensional	Objects which can be measured in three directions (e.g., length, width, and height)
AC	Alternating Current	Electrical current with fluctuating magnitude and direction
ANOVA	ANalysis Of VAriance	Statistical procedure for analysing differences in means
API	Application Programming Interface	Software connection between computer programs
App	Application	Software design for use on mobile devices
AR	Augmented Reality	Superimposition of computer-generated objects onto the user's view of the real world
AV	Augmented Virtuality	Real time representation of the current state of real-world elements in a virtual environment
CAD	Computer Aided Design	Software used to produce 3D models or 2D technical drawings

CERN	European Council for Nuclear Research	Research centre for particle physics, nuclear and high energy physics
CMS	Condition Monitoring System	A system of sensors and analysis used to assess the condition of equipment
CPS	Cyber Physical System	Mechanism controlled and/or monitored by a computer-based system
CSS	Cascading Style Sheets	Defines formatting and display elements for web pages
ER	Error Rate	Number of errors made
GATM	General Assembly Task Model	Splits assembly tasks into 4 different components – locating, picking, locating position, and assembling
GDPR	General Data Protection Regulation	EU framework for the processing of personal data
GIS	Geographic Information System	Computer system for storing and displaying position data
GPS	Global Positioning Satellite	Navigation system using signals from satellites to provide geolocation and time information
GUI	Graphical User Interface	System of interactive visual components in a computer system
HCI	Human Computer Interaction	Field of study focussing on how human users interact with computer and IT devices
HMD	Head Mounted Device	Display devices which can be worn on the head
HTML	Hyper Text Markup Language	Mark-up language used to create webpages using tags to define the formatting of page elements
IAR	Industrial Augmented Reality	AR systems designed for use in industrial environments
IMS	Intelligent Manufacturing Systems	Systems of manufacturing which integrate both human and machine capabilities to achieve results
IMU	Inertial Measurement Unit	Combination of accelerometers and gyroscopes used to provide force and angular data
IoT	Internet of Things	Network of physical objects embedded with sensors, software and more
LCOE	Levelised Cost of Energy	Measures lifetime costs of the energy asset over the amount of energy produced, to allow fair comparison of technologies with

		unequal lifespans, capital costs, risk, capacity etc.
MANOVA	Multivariate ANalysis Of VAriance	Statistical procedure for comparison of sample means in multivariate data
MOOCs	Massive Open Online Courses	Web-based courses aimed at large numbers of participants
MR	Mixed Reality	Merging of real and virtual elements in a visualisation
MRO	Maintenance Repair and Overhaul	Fixing and maintaining equipment or facilities
NASA-TLX	National Aeronautics and Space Administration - Task Load Index	Tool for assessing perceived workload associated with a task, developed by NASA
O&M	Operation and Maintenance	Fixing and maintaining equipment or facilities
OST	Optical See Through	AR systems that use optical techniques to project virtual images onto the real world
PDF	Portable Document Format	ISO 32000 standard files format for fixed layout documents
PHP	PHP: Hypertext Pre-processer	General purpose scripting language
PICOC	Population, Intervention, Comparison, Outcomes, Context	Structure for carrying out systematic literature reviews
PPE	Personal Protective Equipment	Equipment to protect users from health and safety risk
Q-Q Plot	Quantile-Quantile Plot	Graphical method for comparing probability distributions
QUIS	Questionnaire for User Interaction Satisfaction	Tool to assess satisfaction with user interfaces
SEUPB	Special EU Project Board	Cross-border body facilitating research in the regions of Western Scotland, Northern Ireland, and Ireland
SLAM	Simultaneous Localisation And Mapping	Constructing/updating a map of an unknown environment whilst also keeping track of the current location of the agent within that map
SMEQ	Subjective Mental Effort Questionnaire	Questionnaire used to determine mental effort required to complete a task

STEM	Science, Technology, Engineering, and Mathematics	Interdisciplinary education in the fields of Science, Technology, Engineering, and Mathematics
SUS	System Usability Scale	Standardised questionnaire for assessing usability of industrial systems
TAM	Technology Acceptance Model	Theory which models how users accept and use novel technologies
TCT	Task Completion Time	Time taken to fully complete a given task
TORQUE	Tiny, Open-with-Restrictions courses focused on Quality and Effectiveness)	Variation on the concept of MOOCs, consisting of very short videos, questions, tasks, and forums
TRL	Technology Readiness Levels	Method of estimating maturity level of technologies
Tukey's HSD	Tukey's Honestly Significant Difference	Statistical test for making multiple pairwise comparisons of means
UI	User Interface	The part of the system with which the user may interact
UNED	National University of Distance Education	Spanish public university providing distance learning
UoS	University of Strathclyde	UK Higher Education institution in Glasgow
UX	User Experience	Overall experience by the person using the technology
VR	Virtual Reality	Computer generated simulation of a 3D environment which the user can interact with
VST	Video See Through	AR systems that present video combination techniques to merge the real and the virtual
WIMP	Windows Icons Mice Pulldowns	Common set of software and hardware features used in computing

1 Introduction

This chapter introduces the topic of research, defining a starting point for the literature search, which can be found in Chapter 2. A background to the context of the project and the wider programme under which it falls is also provided in order to give a better understanding of how and why the research topic was chosen.

1.1 Research Aim

The aim of this research is to investigate how **Augmented Reality (AR)** technologies - which combine the virtual and real worlds - can be effectively deployed in manufacturing and engineering to improve performance.

The initial inspiration (explained further in Section 1.3) was offshore wind turbine maintenance. Due to their inaccessibility and the cost of vessel hire, they make an excellent target for process improvement activities, as there is potential for a large return on investment. However, as the research progressed, it became clear that many of the benefits of this technology applied equally across much of the manufacturing industry, and so a more general target was taken to the research project.

1.2 Research Context

This thesis was one of twelve PhD projects that formed the Renewable Engine programme (Renewable Engine, 2018). Renewable Engine was a **Special European Union Project Board (SEUPB)** programme, funded through INTERREG to encourage cross-border research and collaboration between the regions of the West of Scotland, Northern Ireland, and the border counties of the Republic of Ireland. It was a collaboration between four academic institutions – the University of Strathclyde, Queens University Belfast, IT Sligo, and the lead partner, South West College, Cookstown – plus Invest Northern Ireland and the mid-Ulster council. Each of the PhDs worked with a small to medium-sized manufacturing company, to carry out research and innovation in the renewables manufacturing sector. The projects aimed to produce research on technologies that fall at levels 3-5 on the **Technology Readiness Levels (TRL)** scale (Figure 1.1).

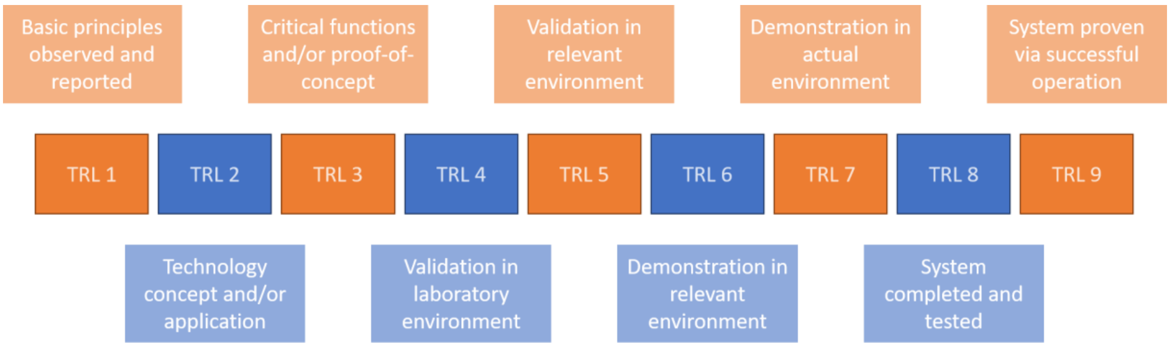

Figure 1.1 – Technology Readiness Level Meter, based on the work of (Mankins, 1995)

The academic partner for this PhD was the University of Strathclyde, and the industrial partner was *Booth Welsh* (Booth Welsh Automation Ltd, 2020). *Booth Welsh* is an engineering services company based in Irvine; Ayrshire, Scotland who are aiming to expand their Industry 4.0 capabilities through this PhD. Industry 4.0 refers to a new generation of digital manufacturing technologies with a focus on embedded intelligence and automation. *Booth Welsh* have existing expertise in many areas of Industry 4.0, including Systems Integration and Simulation (Booth Welsh Automation Ltd, 2019), but were aiming to further develop their knowledge of **Augmented Reality (AR)** to offer additional training and maintenance support to their engineers and clients, by exploring the use of AR technologies in the maintenance of renewable energy assets.

1.3 Project Motivation

Offshore wind farms are now a reliable and significant part of the UK energy mix, making up 11.8% of total electricity generation and around 28% of renewably generated electricity in the first quarter of 2021 (Spry, 2021). Recently there have been large reductions in the **Levelised Cost Of Energy (LCOE)** (average cost per MWh of electricity generated over the lifetime of the generating plant (Crown, 2016)) as turbine sizes and efficiencies increase. Nevertheless, there is still pressure to make further cost reductions to achieve the goal of subsidy-free energy production. In September 2019, the UK Government announced an ambitious administrative strike price of just £39.65/MWh for the years 2023/24. While new offshore wind installations such as Dogger Bank are predicted to meet or even exceed this target thanks to their larger capacity and economies of scale, existing farms with older technologies have higher costs but will remain part of the UK energy mix for years to come (Department for Business Energy & Industrial Strategy, 2020). This puts wind turbine manufacturers under increasing pressure to reduce their production costs. With **Operations and Maintenance (O&M)** typically consisting of 18-23% of the LCOE (Tavner, 2012), maintenance is a key area for cost reduction in offshore wind.

This cost is due in part to the difficulty in accessing remote renewable assets. With UK wind farms being an average of 16km from shore in 2017 (Department for Business Energy & Industrial Strategy, 2018), even small failures can result in large downtimes while the maintenance crew travel to the asset. There are also an increasing number of ‘non-access’ days (times at which turbines are inaccessible due to wind or wave height) as offshore wind farms are constructed further from shore (Fox and Hill, 2018). Considering all this, it becomes clear why offshore wind farms have such low asset availability (80.2%) in comparison to their onshore counterparts (95-97%) (Dinwoodie and McMillan, 2017). It is important to improve right first-time performance on maintenance operations to reduce the number of offshore trips required.

Furthermore, despite recent works in the field of signal processing and **Condition Monitoring Systems (CMS)** as early warning fault detection (Butler et al., 2013), modern wind turbines are so large and complex that even sophisticated CMS have high uncertainty so operators still rely on visual inspection before performing repairs (Dinwoodie and McMillan, 2017). This means operators cannot always be certain which tasks they will be performing until they arrive on site. At present, technicians tend to rely on tacit knowledge and experience to perform these tasks, but for more unusual or complex tasks they may have to search through large amounts of diagrams and documents to find the information required if indeed the documentation has been stored correctly. Due to the difficulty of mentally translating two-dimensional diagrams and text into the real-world context, operator experience is vital for effective and efficient task completion. Such experience can easily be lost when long-term members of the team leave or retire. This means extra training and supervision is required by novice maintenance technicians, who have not yet gained the experience needed to recognise and remember maintenance sequences. Therefore, a method of quickly accessing a variety of information and communicating tacit knowledge would be very beneficial.

The high cost of lost production associated with offshore wind maintenance activities makes a very compelling case for any technologies or innovation that promise to reduce downtime. This makes industry a good candidate for implementing AR as any expenditure on equipment and development is offset by larger potential savings, and a timely return on investment is more likely. However, many of the fundamental problems facing the offshore wind industry – task complexity, limited access, cost of downtime, capturing tacit knowledge and a suitably skilled workforce – are common to much of the manufacturing industry. Lost production due to downtime is a problem across sectors, and the skills gap has been a pervasive issue across the engineering industry for many years (Kumar, 2014). Therefore, the research presented in this thesis will consider activities across the spectrum of engineering sectors.

Industry 4.0 is the term used to describe the 4th Industrial Revolution, centred around **Cyber-Physical Systems (CPS)**, which interconnect physical and computational assets for increased production efficiency (Lee et al., 2015) and **Intelligent Manufacturing Systems (IMS)**, which use machine learning techniques to self-regulate within process parameters (Krajcovic et al., 2013) as shown in Figure 1.2.

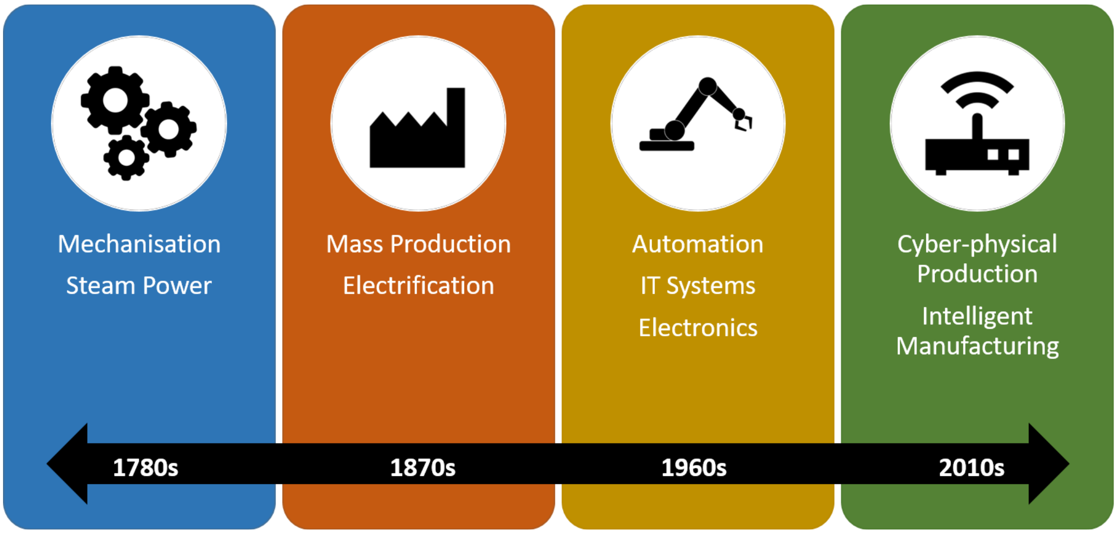

Figure 1.2 - Industrial Revolutions and their defining technologies

The next generation of manufacturing technology is based on the idea of autonomous communication between machines, automated decision-making and embedded intelligence, and the blurring of the line between virtual and physical assets. As shown in Figure 1.3, Industry 4.0 is characterised by nine key technological pillars (Gilchrist, 2016), one of which is Augmented Reality.

Clockwise from top: Augmented Reality, Cloud Computing, Internet of Things, Integrated Systems, Simulation, Additive Manufacturing, Autonomous Robots, Big Data, Cybersecurity

Figure 1.3 - The 9 Technological Pillars of Industry 4.0

This research will focus primarily on Augmented Reality as a driver for improved manufacturing and maintenance operations.

1.4 Thesis Structure

This thesis is presented in ten main chapters, plus Appendices A - G, which contain supplementary materials such as datasets and surveys. All data in the main body of the thesis is provided to three significant figures unless specified otherwise. A list of key acronyms and abbreviations are provided on page xxiii, and are highlighted in **bold and blue** where they first appear in the text.

In **Chapter 1**, the research context for the thesis is outlined, and explanations are provided as to why this particular topic of research, Augmented Reality support for manufacturing and maintenance activities, was chosen. **Chapter 2** gives a comprehensive background to how Augmented Reality works, both technically and cognitively. A critical analysis of existing research regarding its use in industrial settings is provided, which led to the identification of aims and objectives for this thesis.

Chapter 3 outlines the philosophical assumptions underpinning decisions in the research design, while **Chapter 4** outlines the specific approach taken to research and experimentation in this thesis, including important background work to determine key experimental parameters.

Chapter 5 discusses the development of an **app (application)** to deliver AR instructions during experiments. It also provides the results of Trial 0, a preliminary study to demonstrate the functionality of the application and evaluate the initial plan for research methodology.

Feedback from Trial 0 was used to refine the methods used in **Chapter 6**, where a series of experiments (Trials 1-3) were carried out to determine the most effective way to display and interact with AR procedural instructions.

Building on the findings of Trials 1-3, **Chapter 7** outlines a further study (Trial 4) undertaken to explore the influence of novelty and experience on user performance when following AR guidance.

Chapter 8 addresses the topic of AR in engineering training and education by presenting a novel application of **Mixed Reality (MR)** to allow remote learning in vocational subjects (Trial 5). In addition, Trial 6 in **Chapter 9** shows how AR can be used to rapidly upskill novice users in Industry 4.0 technologies.

Finally, **Chapter 10** is a summary of all the research contained in the thesis, and how the results of the research can be implemented practically in industry. Suggestions are made for future research directions.

2 Literature Review

2.1 Introduction

This research is motivated by a need to reduce time and cost associated with industrial maintenance activities, and to improve right first-time performance. Though initially inspired by the offshore wind industries, as discussed in 1.2, it was clear that the themes identified in offshore wind are also applicable across a variety of different sectors of the engineering and manufacturing industries. This chapter (Chapter 2) presents a literature review of research in the field of AR for the manufacturing and engineering industries more generally, though it also covers the topic of offshore wind in more detail.

Firstly Section 2.2 describes the technological developments that have led to today's AR technologies, then Section 2.3 gives an overview of the technologies that fall under the umbrella term of AR. Various options for AR devices, graphics and object **tracking** are discussed to demonstrate how they can display 3D content in the real world. Section 2.4 describes applications in which AR technology has been used within today's workforce with the aim of improving performance and user experience.

Section 2.5 conversely explains how AR works on a cognitive level, describing the learning theories that underpin the use of AR in an instructional or educational context. Next, significant studies in the field of AR are explored. Section 2.6 focuses on how merging the virtual and physical can pave the way for new learning experiences to help train the workforce of the future.

Finally, the information gathered during the literature review helped to identify gaps in the current body of knowledge (Section 2.7) to identify four main objectives of the research (Section 2.8).

2.2 History of Immersive Technologies

AR technologies have gained popularity in recent years as technology has improved and costs reduced, yet the underlying concepts have existed for many years.

The first step in the history of AR was the development of 3D imaging. As early as the 1830s, people were experimenting with stereoscopic technologies which work by showing different images for each eye, which when combined appear to form a single 3D image. An example of this can be seen in Figure 2.1.

Figure 2.1 – An example of an early stereoscope device

It was then not until the 1950s that the first **Virtual Reality (VR)** machine was developed, known as the Sensorama. It used stereoscopic technologies to present 3D video to the user, as well as sound, smell, and vibration to create a fully immersive technology.

The first augmented reality devices appeared in 1968 – a headset (Figure 2.2) developed by Ivan Sutherland, that used miniature cathode ray tube displays to show 3D images and videos (Sutherland, 1968). It was also able to update in real time as the user moved their head.

Figure 2.2 – Ivan Sutherland's 1968 prototype headset *(photo used with permission from (Pargon, 2008), under CC BY 2.0)*

At this stage, the technology was not advanced enough for commercial use, being too heavy and cumbersome for use outside of the lab. Though some advancements were made in the meantime, driven largely by military needs, it was not until the late 2000s that commercial applications begin to emerge.

As technology continued to improve, the cost and size of components being driven down by the massive demand for mobile phone technology, VR and AR devices became more advanced, more powerful and more affordable. A wide range of devices now exists, as shown in Figure

2.3. Starting with high end, dedicated headsets that can take live data and visualise it in high quality 3D renders at a specific point in time and space based on computer vision algorithms; all the way down to low-cost stereoscopic viewers such as the Google Cardboard, which can convert even budget smartphones into VR/AR viewing devices.

(a) ***(b)*** ***(c)***

Figure 2.3 – Examples of current AR devices *(a)* Magic Leap AR headset *(photo by Bram Van Oost, used with permission under Unsplash license)***, *(b)* AR app viewed on a smartphone phone** *(photo by Mika Baumeister used with permission under Unsplash license)***, and *(c)* a Google Cardboard AR viewing device**

With such a wide spectrum of price points and capabilities now available commercially, it is an ideal time for industrial AR to be adopted on a large scale.

2.3 Technical Background to AR

Before discussing AR, **Mixed Reality (MR)** should be defined. MR is a generic term for technologies that combine real entities with virtual elements (Milgram and Kishino, 1994). Milgram's Reality-Virtuality Continuum (Figure 2.4) is a taxonomy of Mixed Reality concepts.

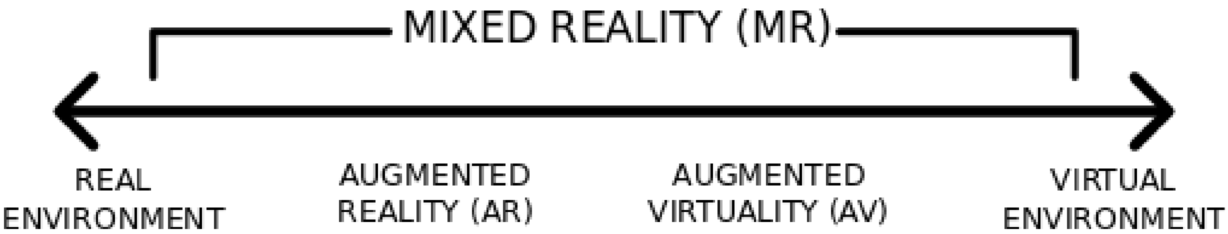

Figure 2.4 – Simplified representation of the Reality-Virtuality Continuum, (Vincenti, 2011) used with permission under Creative Commons license

It classifies various display technologies, ranging from the fully virtual (immersive, computer-generated environments in which the user only interacts with virtual items) to fully real (a direct view of the real world) (Milgram et al., 1995). The term Mixed Reality describes any display technology that falls between the two extrema of the continuum. Figure 2.5 shows some examples of these technologies.

(a) ***(b)*** ***(c)***

Figure 2.5 - Examples of immersive technologies *(a)* Virtual Reality *(photo by XR Expo used with permission under Unsplash license)***, *(b)* Augmented Reality** *(used with permission under Unsplash license)***, and *(c)* Augmented Virtuality** *(Bruder et al., 2009) used with permission © 2009 IEEE*

Technologies such as Virtual Reality, Augmented Reality and **Augmented Virtuality (AV)** all lie along this spectrum, as subsets of MR. VR usually refers to immersive, entirely computer-generated environments, where the user only experiences and interacts with virtual objects. AR, by contrast, describes technologies where the user experiences the real environment (either directly or resynthesized on the display) enhanced with virtual objects or information. AV is the opposite – a virtual environment in which the user may interact with certain real-world entities.

This work focuses mainly on AR technologies, as AR is generally more suitable to industrial settings due to the fact the user can still perceive the real world around them. VR, in contrast, would completely block the users' view of the real world, so is more suited to training applications where the user's surroundings can be controlled and made safe.

AR can broadly be considered any technology that combines both the real environment and virtual information in a single view. But certain other criteria must also be met - Azuma's definition, now widely accepted in the AR research community, stipulates that AR systems must be interactive in real-time and spatially register virtual contents in **Three Dimensions (3D)** (Azuma, 1997). This separates AR from the simpler head-up displays that show static, screen-locked content tied to a location relative to a screen, rather than relative to the real world.

As AR technologies have matured and dedicated devices became more readily available and affordable, **Industrial AR (IAR)** research has become a topic of significant interest over the past few years. The exact structure and components of AR systems varies (see Section 2.3.3), but the basic building blocks are usually similar, as shown in Figure 2.6.

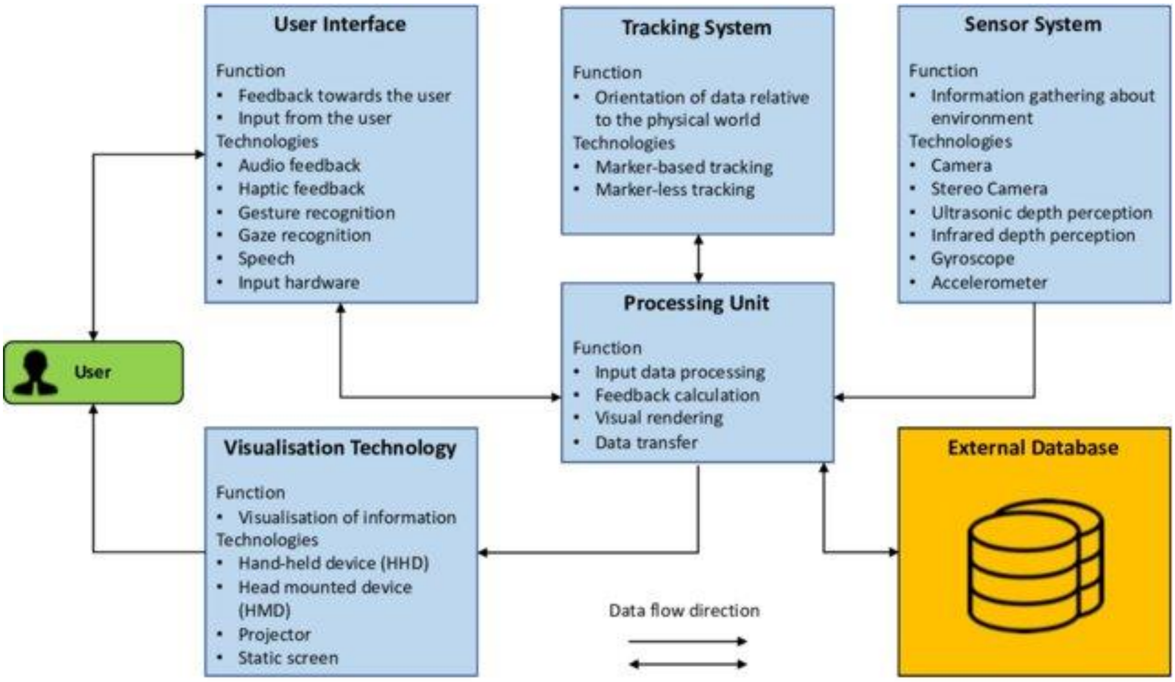

Figure 2.6 - Block diagram to show key modules in a generic AR system (Masood and Egger, 2020).

Reprinted from Computers in Industry, Volume 115, 103112, Tariq Masood and Johannes Egger, 'Adopting augmented reality in the age of industrial digitalisation', pg. 3, 2020, with permission from Elsevier

A tracking and registration module (see Section 2.3.1) finds the device's position and orientation as well as the position of key objects, allowing virtual content to be accessed from a database and rendered in the correct location relative to the user's viewpoint. Depending on the display type, (see Section 2.3.2) the user may either view the real world directly with virtual content optically superimposed, or else video mixing techniques may be used to let the user observe a digitally altered video stream of their surroundings.

2.3.1 Registration and Tracking

A key feature of AR is that virtual objects are registered spatially in 3D, rather than relative to a position on screen (Azuma, 1997). This requires both registration and object tracking.

Registration refers to the spatial and temporal alignment of virtual objects in the real world, typically achieved through a combination of **tracking** – the measurement of an object's pose relative to the environment – and **localisation** – determination of an object's pose relative to a global reference frame (Calloway et al., 2017).

Camera pose tracking typically uses **Global Positioning System (GPS)** and **Inertial Measurement Unit (IMU)** sensors to calculate the position and orientation of the camera (same as user viewpoint) in the world frame, and then object tracking is performed to calculate the pose of objects of interest in relation to the real world. A 4x4 homogenous transformation matrix describes the transformation between the camera's coordinate system and the object frame. The transformation matrix is then used to add virtual objects into the real scene with the correct pose in three-dimensional space (Grubert et al., 2017).There are three main tracking methods used for object tracking:

- **Sensor-based**, a fast and robust method in which IMU, GPS, or structured light may be used to find real-world locations for content to be rendered;
- **Vision-based**, a high accuracy technique in which computer vision tools are used to recognise real objects and virtual information is rendered over the top;
- and **Hybrid**, which combines both sensors and vision tools to create a tracking system which is both robust and accurate (Nee and Ong, 2013).

Vision-based tracking is generally the most popular, as GPS and other sensor-based tracking techniques often achieve poor accuracy in indoor applications (del Amo et al., 2018), therefore only vision-based tracking will be discussed going forward. Vision tracking itself is split into two categories:

- **Marker-based Tracking**, where a distinctive fiducial marker (similar in appearance to a QR code) is applied to the object which can then be recognised and matched to corresponding virtual content (Sagitov et al., 2017);
- and **Natural Feature Tracking** (or marker-less tracking), where the AR system learns to recognise key features of the actual object based on 3D models or images of the object.

Marker-based tracking is a fast technique and robust to illumination changes but requires a priori access to tracked objects. Marker tracking is also prone to occlusion failure and tracking often fails catastrophically if the camera's view of the marker is partially or fully obstructed (Sagitov et al., 2017). Natural feature tracking, requires a priori knowledge of the tracked object but not necessarily physical access. It has poorer illumination robustness however and requires large datasets of distinctive key points to learn to recognise features (Kasapakis et al. (2018), Daponte et al. (2014)). Marker-based tracking is more appropriate in poor or variable lighting conditions. Alternatively, it is often used when the appearance of the environment is not important. Therefore, it is well suited to industrial environments such as offshore wind turbines. At present, natural feature tracking is only really suited to more controlled environments with good lighting and little variation.

This research takes place indoors on small assemblies, so a vision-based approach was chosen for accuracy and precision. In this case, marker-based techniques were selected for their simplicity, robustness and low computing requirements, to allow fast response even on mobile devices with limited processing power. This was carried out using A-Frame's image tracking algorithms to recognise simple black and white markers, created using a marker training website called AR.js (Etienne, 2019) to generate the corresponding pattern files.

A more resilient solution may be to combine several vision tools, for example marker recognition with **Simultaneous Localisation and Mapping (SLAM)** (Taheri and Xia, 2021), which would make the tracking solution more robust to occlusion of markers. The marker would provide an initial anchor for the content, while SLAM algorithms use features of the real world to maintain an estimate of camera pose, allowing content to be visualised even while the marker is temporarily off screen. When the marker returns to view, the position can be updated to ensure accuracy. However, this method was not used in the following experiments for the sake of rapid development of the app, and minimising processing power. This was particularly important as many of the studies presented in this thesis (Chapters 7 - 8) are reliant on the users' own devices and as such the device capabilities are unknown. So while the benefits of a SLAM based algorithm are clear, marker tracking was ultimately selected for the sake of computational efficiency when deploying to a wide range of devices with little to no information on hardware/connectivity requirements beforehand

2.3.2 Graphics and Display

AR displays can be split broadly into two categories of display type (Dini and Dalle Mura, 2015):

- **Optical See Through (OST)**, in which the user has a direct view of the real world and projected virtual objects, using optical combination techniques;
- and **Video See Through (VST)**, where a camera array captures a live video stream of the real environment and video mixing is used to combine virtual renderings into the video stream.

VST displays generally suffer greater latency due to an increased data transfer requirement, however, it is less noticeable than in OST devices as the video stream can be delayed to synchronise it to the content (del Amo et al., 2018). This delay can of course cause issues in industrial environments, where it may be preferable to have a direct view of the user's surroundings, as viewing a delayed stream of the workspace may constitute a significant hazard.

2.3.3 Hardware Devices

AR can be deployed on many types of devices. Early systems were often PC-based (Palmarini et al., 2018), making use of webcams to capture video streams of the real world, thus limiting them to VST type displays. PC-based systems are also limited in terms of mobility as it is awkward and difficult to move them around, particularly in busy industrial environments. More recently, mobile technologies have improved such that mobile phones and tablet devices have become popular implementations of AR. They are highly portable, are familiar to use for most people, and can easily be ruggedized or made inherently safe for use in hazardous environments. Again, however, these systems are limited to VST type displays and cannot be used hands-free without significant adaptation.

Figure 2.7 - mobile phone with Google Cardboard AR/VR viewer

Head-Mounted Displays (HMD) typically consist of a screen worn in front of the eyes, mounted using a headband. VR displays are sometimes adapted for use with AR content using the camera to capture video streams of the real world, effectively turning them into VST devices. However, an increasing number of purpose-built OST AR devices are now available on the market, which use a direct view of the world combined with semi-transparent half-silvered screens to present digital information into a live view of the real world. HMDs allow hands-free operation, making them well suited to complex tasks requiring frequent reference to information such as instructions, sensor readings etc. An example is shown in Figure 2.8.

Figure 2.8 – Example of a Head Mounted Display, Microsoft HoloLens, 1st generation

PC-based in-situ projection, also referred to as Spatial Augmented Reality has also been explored by some researchers (Dini and Dalle Mura, 2015). In Spatial AR systems, processing is carried out by the PC and used to control a series of lights or 3D projections, which displays information directly onto the work piece, or work area. Volmer et al., 2018 suggest Spatial AR is a good way to avoid some of the pitfalls of HMDs and mobile AR is an affordable and already familiar technology to most.

By detaching the display from the user and integrating it into the environment, the system is no longer reliant on stable lighting and tracking systems, so performance issues are reduced. Spatial AR displays (as demonstrated in Figure 2.9) are only suitable for tasks that are confined to a small area, require significant investment in equipment that is limited to a small area, and are prone to occlusion issues when the user is working in the display area. Perhaps more significantly, these displays require high investment, as they are specific to each asset.

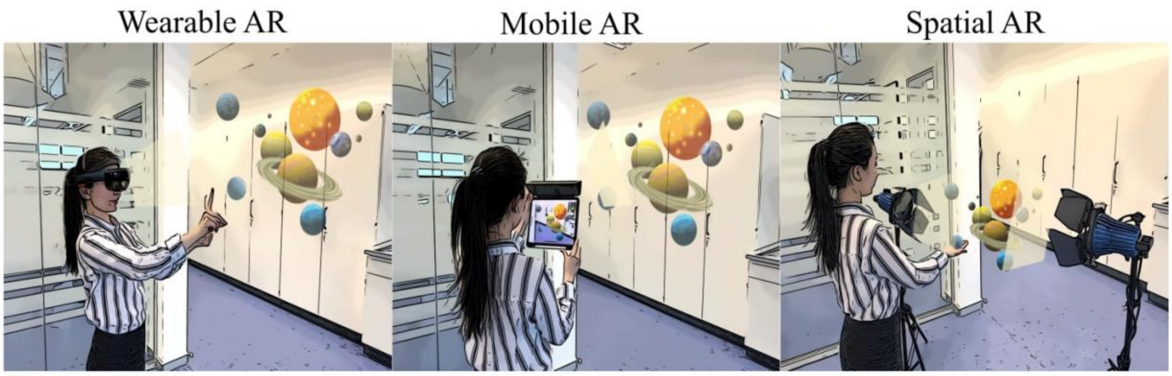

Figure 2.9 –Wearable, Mobile and Spatial AR, CC BY 4.0 (Makhataeva and Varol, 2020)

2.3.4 AR Application Development

An **application (app)** is a computer program designed for use on a mobile device. Apps may be native (designed for a specific platform and operating system), or web-based (accessed via web browser). These two possible methods of hosting AR content was compared in Table 2.1.

Table 2.1 - Pros and cons of native app vs web implementations of AR

FEATURE	NATIVE	WEB
Marker recognition	✓	✓*
Voice commands	✓	✓*
Gesture control	✓	✓*
Live sensor input	✓ (custom extensions)	✓
Access databases	✓	✓
3D models	✓	✓
Open source	✗	✓
IoT/WoT integration	✗	✓
Deployment	To each machine separately	Via web browser
Data connection	May be required	Always required
Cross platform	✓ (separate apps for each)	✓ (browser based)
Languages	Typically C#, C++	JavaScript, HTML

*libraries available

Native AR apps are usually created in dedicated software. Often this is a game engine, such as Unity (Unity Technologies, 2021) or Unreal (Epic Games, 2021), because they offer a relatively easy way to create content of high visual quality in 3D environments with a user-friendly **Graphical User Interface (GUI)** for frequently used elements, while more complex behaviours can be added using custom scripts in C# or C++. High-level programming languages can also be used to create native AR apps from scratch, though this is much more labour intensive. They are built for a specific platform (e.g., iOS, Android, Universal Windows Platform) and though they can be deployed via the internet, they must still be installed onto each device they will be used on.

In contrast, web apps are browser-based solutions that can be accessed and deployed via the web. They are cross-platform, require no installation, and can be used on almost any device so long as it has a camera and a compatible web browser. The benefit of this is that the app is much more flexible, can be updated without having physical access to any device and allows various device types to be deployed, dependent on the situation.

This could be valuable in the field of wind turbine maintenance where a variety of different environments (in the nacelle, in the hub, on the viewing platform) may demand different types of solution. Moreover, in such a remote and potentially hazardous environment, it provides users with a backup source of information. For instance, if a technician was using a hands-free HMD device that malfunctioned or was damaged, they could simply pull out their phone to finish the operation. It may be slightly less convenient than their original device, but significantly easier and less time consuming than having to come back to shore to obtain a replacement.

Web apps can also be readily integrated with **Internet of Things (IoT)** technologies if desired, which could offer an easy way to access live sensor data remotely or on-site. Whilst cybersecurity is considered beyond the scope of this PhD, it is worth noting that one disadvantage of a web app approach is that there may be some privacy or cybersecurity concerns over hosting content over the web. However, this is overcome in the same way any website content can be protected – it can even be kept on the company's intranet rather than the public web. Another reason for hesitation in adopting this approach may be that it relies heavily on a data connection. While data connection is considered beyond the scope of this PhD, it should be noted new offshore wind farms are increasingly likely to be connected to 4G networks. Communication delays may still be an issue, particularly if much of the computation is offloaded to a cloud server, which would affect real-time performance of an AR app.

Typically, web technologies can be split into server-side (backend) and client-side (frontend). The server-side technologies include the server itself, a hosting platform, and any databases used to contain app information. Traditionally, server-side scripting is often done using **PHP: Hypertext Pre-processor (PHP)** that runs on the Apache webserver. On the client-side are languages used to control how content from the web browser is displayed. Almost all websites use JavaScript to control the behaviour of webpages. Several AR specific JavaScript libraries are now available to assist with the creation of Web AR apps.

2.4 AR in Assembly and Maintenance

According to Havard et al. (2015) AR for support of maintenance activities falls into two broad categories – Assisted Maintenance and Guided Maintenance.

In Assisted Maintenance style applications, AR can bring an expert based at a remote location virtually to the site, to advise or troubleshoot. This typically happens via screen sharing of the AR device, allowing both the on-site technician and the remote expert to annotate the live view to help convey information about the scenario in 3D. This has the benefit of allowing a single expert to advise on several sites, without being co-located which can be particularly useful in an offshore wind setting for example, where sites are disparate and difficult to access.

Conversely, Guided Maintenance uses AR devices to provide additional contextual information to aid maintenance tasks. This could be instructions, live data streams or more, provided right at the point of use, within the 3D environments. This form of AR instruction forms the basis of this research as it provides a completely new paradigm for delivering instructional information and guidance.

The bulk of the work in this area focusses on assembly and disassembly tasks, such as the motionEAP project (Funk et al., 2016) which successfully demonstrated an IAR assembly guidance system that reduced error rates in both cognitively impaired and non-impaired workers. In another example, Fiorentino et al. (2014), saw reductions in task completion time and error rate when using screen-based AR to maintain motorbike engines.

These studies all demonstrate tangible benefits of implementing AR; however, they tend to focus on very controlled environments such as laboratories or assembly lines. In the field of offshore wind, Quandt et al. (2018) presented a system architecture for inspection of electronic components; however, the performance benefits were not quantified.

2.4.1 Industrial AR and Performance

The most common use for AR in the field of maintenance is to guide assembly/disassembly tasks (Palmarini et al., 2018). The AR interface can be a substitute for traditional paper-based instruction manuals, to deliver task guidance directly in the user's line of sight in the form of text, **2D**/**3D** models, or animation.

Kosch et al. (2017) showed that spatial AR in manual assembly could be used to support users of various experience levels in manual assembly tasks. For novice users, in-situ projection AR provided the consistent guidance they needed to perform unfamiliar tasks faster and more accurately, whilst even maintenance experts reported that they recognised the value of AR systems to help them train novices with minimal human supervision. Funk et al. (2015a) also explore the benefits of spatial AR to cognitively impaired workers, finding AR provided better support for them to complete tasks quicker and with fewer errors, thanks to a perceived reduction in mental demand. Work on in-situ projection-based AR confirmed a reduction in errors and task completion time, of 20.3% and 83.3% respectively, finding it was especially beneficial for tasks involving locating and selecting components (Fiorentino et al. (2014), Uva et al. (2017)). De Amicis et al. (2017) suggest that PC and Webcam based AR has can also be successfully used to guide assembly processes, though their case study made no comparison to other instruction methods.

Similar investigations have also been made using wearable AR devices. Pierdicca et al. (2017) demonstrated the benefits of AR guidance in assembly using Vusix M100 smart glasses, which allows operators to use the device even if both hands are required to carry out a task. Whilst both experienced technicians and inexperienced trade show visitors found the use of AR reduced execution time, there were drawbacks associated with the chosen hardware. Radkowski and Ingebrand (2017) have used the Microsoft HoloLens to deliver instructions to mechanical engineering students to guide them through the assembly of a piston motor. Using a five-point Likert scale to analyse the student's experience of using the HoloLens, it was found that most considered it useful though a few, especially glasses wearers, did not enjoy wearing the device. Although this was a useful demonstration of improvements in HMD technology, no specific performance benefits were measured.

Deshpandel and Kim (2018) used the Microsoft HoloLens HMD to investigate the cognitive benefits of AR assembly guidance in understanding spatial relationships, rather than visual assistance for search tasks as in previously discussed works. They compared the performance of people using standard paper instructions to those using the HoloLens to construct ready-to-assemble furniture, finding a statistically significant reduction in assembly time only for simple tasks. No significant reduction in errors was found for either simple or complex tasks. For complex tasks, there was improved spatial understanding, mental representation, and a reduced cognitive load. This suggests promising benefits for the field of industrial assembly where assemblies often have many parts and lengthy instructions.

Industrial maintenance is a good candidate for AR guidance, as activities in this field can be expensive and high pressured, and time spent searching for instructions has been cited as a key cause of employee stress and poor performance (Erkoyuncu et al., 2017).

Palmarini et al.'s 2018 systematic review of Augmented Reality applications in maintenance suggests that as of 2017, the current state of the art in AR technology is still not mature enough to comply with industrial requirements for robustness and reliability. They recommend that future work should focus on making hardware more mobile, improving tracking robustness, development of flexible authoring tools and creation of adaptive systems that use feedback from users to improve system performance. Henderson and Feiner (2011) applied AR to maintaining tank turrets in the field. In the AR condition, they used a VST HMD with external tracking cameras and a wrist-worn controller. This was compared to a notebook computer used to display **PDFs (Portable Document Format)**. Though they found little difference between the conditions, it was concluded this might be due to a lack of understanding of what makes an effective AR instruction. Additionally, technological limitations of weight and battery life were noted. With modern technologies, these issues should be minimised.

However, other research contradicts these findings, reporting significant success. For example, Re and Bordegoni (2014) created an AR system to support and monitor workers in food packing. They speculate that by providing additional contextualised information to users, there is less need for on-site experts and so skilled resource can be distributed more effectively using AR as a form of remote communication. However, the study did not explore any specific or quantitative benefits. Golanski et al. (2014) also successfully implemented a mobile-based AR application to support technicians in aircraft maintenance. Whilst it was well-received and met all initial assumptions, feedback indicated that constantly holding the device was cumbersome and the Human Machine Interface needed finessing to be more user-friendly.

Fiorentino et al. (2014) had great success applying screen-based AR to the maintenance of motorbike engines. Both task completion time and errors reduced in comparison to traditional instructions. In particular, there were benefits during the part localisation and selection phases of the tasks. This is consistent with work by Funk et al., 2015b, who developed the **General Assembly Task Model (GATM)**. The GATM splits assembly tasks into four components –

‘locate’, ‘pick’, ‘locate a position’, ‘assemble’ – to draw detailed conclusions about where the benefits of AR are most notable. Their results suggest that AR can have the most significant improvements on the time spent on ‘locate’ and ‘locate position’ phases but has little effect on ‘pick’ and ‘assemble’ phases.

Marino et al. (2021) presented a case study at an oil and gas company. Users inspected a large auxiliary baseplate system, identified and annotated any discrepancies, then communicated this back to the technical office. Marino et al. found users made very few errors, suggesting the tablet-based AR system was very intuitive to use, and that discrepancies were detected very quickly. Additionally, users expressed positive opinions and rated it an average of 85 on the System Usability Scale, where 70 is considered ‘acceptable’.

Petrone et al. (2021) made comparison between AR and video recordings for assembly of 3D puzzle balls. They found that instructions delivered over AR headsets resulted in higher accuracy and efficiency than simple videos, though this effect was more notable when tasks were more complex, due to the learning curve associated with operating the headset.

Therefore, it seems AR shows great promise for reducing cognitive load, task completion time and error rate, particularly in complex tasks and those requiring high locational accuracy, such as industrial maintenance and manufacturing.

2.4.2 User Acceptance of IAR

Aside from technical capabilities, it is important not to forget the role of the user in IAR systems. Human-centred technologies such as these can quickly become failures if those who have to use them daily do not value them.

The Factory2Fit project (Aromaa et al., 2019) examined four key aspects of Industry 4.0 by gathering opinions of factory workers in Finland and Germany. The project proposed that AR glasses could be used for visualisation of information pulled from other software, or in its own right to produce interactive interfaces to highlight targets and aid production. Factory workers were generally positive towards the technology and saw applications in training and maintenance but had concerns over health and safety. Therefore, minimising occlusion of immediate surroundings and ensuring any equipment used is suitable for environmental conditions are important factors to be considered in AR system design. Aromaa et al. also investigated user acceptance of mobile-based AR in industrial maintenance to share solutions between users. The system was well received, despite concerns over practicalities such as reliable internet connections and cost of the file transfer. In particular, users expressed that it would only be useful if it were possible to integrate with their existing systems. Henderson and Feiner's 2011 experiments on AR documentation for turret repair support these findings, suggesting that despite the shortcomings of the technology available at the time, mechanics are willing to tolerate these limitations if the device provides value.

Kim et al. (2019) explored how user interaction and displays affect performance in picking and assembly tasks, finding that constantly visible graphics-based information improved performance compared to text-based or sometimes hidden content. Both binocular and monocular HMDs were preferred to paper or PDF pick lists, however, this (and many other studies) used young students as participants and only used the devices for a short period. This limits the generalisability of the study, as younger users tend to be more comfortable with new technologies, and ergonomic effects of wearable displays may not be apparent when using devices for just a few minutes.

Some users may have an issue with the social acceptability of wearable devices. An investigation into user acceptability of smart glasses by Rauschnabel et al. (2018) demonstrated that whilst consumers do have concerns over invading the privacy of those around them, HMDs are much more acceptable in the workplace where people are used to being monitored.

Whilst it is important to exercise caution when selecting participants for user acceptability investigations, these studies are generally positive towards AR and wearable technologies. It seems that if the technology can deliver tangible value, users are willing to tolerate minor technical shortcomings in the deployment.

2.4.3 AR in Offshore Wind

Of particular relevance to this project, is the Mer Innovate project white paper (Havard et al., 2015), which suggests AR technology may have significant benefits for offshore maintenance crews, particularly if further research into appropriate hardware and user interaction factors are carried out. However, the Mer Innovate team are clear in their recommendation that standardised authoring tools should be developed to make it easy for expert users to create AR content, regardless of their programming experience. In addition, real operators should test and review AR maintenance procedures on a variety of devices, to test fitness for purpose and discover which platform works best for extended use.

Pargmann et al. (2018) capture wind turbine business and technical data to create a **Digital Twin**, visualized in AR. They adopt an event-driven approach to data processing, where each point of information is encoded with a semantic context, which triggers actions. A Raspberry Pi micro-controller compiled local operational data into a single data stream uploaded to the cloud, whilst SCADA and enterprise data was uploaded directly. This data was semantically encoded in a central IoT engine to form the digital twin along with **Geographic Information**

System (GIS) data to specify asset co-ordinates. Pargmann et al.'s work allowed multiple users to see wind farm-related data in a meaningful and intuitive way. Whilst it explores the idea of sharing this information to wind turbine technicians, it fails to touch on possible **Maintenance Repair and Overhaul (MRO)** activities.

Despite great promise for the application of AR to turbine maintenance shown in these studies, there is still significant room for more statistically rigorous studies, which examine the quantitative benefits and downsides of AR in this particular application (Section 2.8).

2.4.4 AR in Extreme Environments

Mantzios et al. (2014) define an extreme environment to be one that has the potential to cause a physical or mental load to humans, or ones that contain significant hazards. Offshore wind also falls into this category: technicians are at significant risk when working at height and rope access tasks, frequently interacting with high voltage electrical systems, and in an isolated location. They are vulnerable to changes in weather conditions, and have limited access for emergency services. However, it is not a unique working environment – oil and gas platforms face similar challenges of access and communication, nuclear power share criticality of infrastructure that makes right-first-time performance so important, and even certain military environments have similarities with the cramped conditions of the turbine nacelle. Therefore, despite minimal research applying AR to the wind sector, there is much to be learned from the experience of other sectors.

The EDUSAFE project (Mantzios et al., 2014) explores the use of AR in one such environment: the detector caverns of the Large Hadron Collider at **CERN (European Council for Nuclear Research)**. This is a large space, with significant hazards from radiation, and a large amount of complex and unique equipment, upon which a huge amount of funding and research is reliant. Therefore, it is critical to have meticulous instructions allowing right first time maintenance. OST devices are the only acceptable option as a lack of direct visual contact with the environment risks trip hazards in an already dangerous environment. With such complex equipment, accurate registration of virtual content is vital. With this in mind, the EDUSAFE team specify that eye tracking should be developed if possible, to improve accuracy and that the software and hardware should be as lightweight as possible to reduce delays and therefore registration errors in the display of content. Finally, safety gloves are required during all operations, meaning touch interaction is not preferred – alternatives such as tangible and speech-based interfaces are considered more appropriate.

In the field of Oil and Gas, AR is beginning to be applied to support offshore technicians. In many cases, this is through assisted maintenance i.e., sharing their environment with an offsite expert to reduce the number of trips to remote sites. Given that trips can cost $1,500 - $10,000 per incident (similar to the offshore wind where crew transfer vessels alone can cost £2500 a day (Crown Estate, 2010)), this has demonstrated significant cost savings (Meiron, 2019). Schroeder et al. (2017) have also demonstrated the success of guided maintenance instructions in an offshore oil and gas processing plant. Using a web-based interface and on-device graphics processing to reduce communication delays (consistent with Mantzios' recommendation toward lightweight architectures); Schroeder's instructional app uses marker tracking to insert visual content in the correct location. Meiron (2019) also reported a faster training process as AR guided maintenance allows some learning to take place on-the-job, which is critical considering the expanding offshore wind market but the lack of experienced and skilled offshore wind engineers in the UK (Maier, 2017).

Finally, Henderson and Feiner (2011) present an AR system for maintenance of a revolving cockpit in an armoured vehicle, with a very limited working volume of $1m^3$, though infrastructure encroaches on this space leaving a functional work area of around $0.34m^3$. This is significantly smaller than a typical offshore wind turbine, as the LEANWIND reference 8 MW model describes a 20 m x 7.5 m x 7.5 m nacelle (Desmond et al., 2016). However, since safety equipment is worn and encroachment of other structures and equipment, space still tends to feel cramped. Additionally, areas of the tower, hub and blades are barely large enough for a human operator to access. For the armoured vehicle, the small working volume combined with limited Field of View of current devices means users cannot step back to view lots of content at once, so there needs to be a method of directing attention or alerting users to the presence of off-screen virtual content. Henderson and Feiner solve this problem using 2D/3D arrows to identify the location of text and 3D models of tools out of current view. Form factor is also critical in small working areas. Henderson and Feiner developed a custom headset, but technology has since evolved such that off the shelf devices are now sufficiently compact that they can be combined easily with existing **Personal Protective Equipment (PPE)**.

In summary, the key considerations for implementing AR in extreme environments are:

- Physical characteristics – form factor and compatibility with PPE;
- Effective conveyance of information to improve user performance; and
- Accuracy of content registration (minimising communication delays, lightweight architectures, fast and accurate tracking).

2.5 Cognitive Background to AR

While the technical detail in Section 2.3 is critically important, hardware and software are not the only components in an effective AR system – human factors play a role too. Therefore, this section explores how the fields of cognition and psychology intersect with research on AR and digital work instructions.

2.5.1 Effective Learning in AR

Please note: *some of the information contained in this section is based on a previously published paper*[1].

Masood and Egger (2019) found that the most significant advantage of IAR is effective access to information. They revealed that 70% of the pilot projects surveyed started in the previous three years (since 2016), suggesting that this area of research is still in its infancy. Hannola et al. (2018) proposed four methods by which digital learning technology can improve production processes:

- Knowledge discovery through self-learning workplaces;
- Digitally augmented knowledge transfer;
- Knowledge acquisition through mobile learning;
- Worker-centric knowledge sharing.

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[1] *SMITH, E., MCRAE, K., SEMPLE, G., WELSH, H., EVANS, D. & BLACKWELL, P. 2021. Enhancing Vocational Training in the Post-COVID Era through Mobile Mixed Reality. Sustainability, 13, 6144. Adapted with permission under the Creative Commons Attribution License.*

This is supported by Marienko et al. (2020). They suggest that one of the main benefits of AR and VR learning over traditional methods is the ability to personalize learning experiences to individuals and improve the efficiency and effectiveness of their learning. They recommend the use of AR and VR to replicate future work environments, which leads to improved productivity in the workplace when compared to traditional classroom-only teaching.

Additionally, this blend of the real and virtual world in learning can align with the concept of flipped learning—a learner-centred approach to education with a flexible approach to accommodating learning where most content is accessed outside of formal learning spaces, leaving “classroom time” open for more discussions and active learning activities (Saichaie, 2020).

Studies suggest this style of pedagogy can engage a wider range of learning styles, as well as having a positive effect on motivation (Tse et al., 2019) and performance, especially in project-based learning (Sanchez-Romero et al., 2019).

There are several different explanations as to how AR facilitates understanding. Santos et al. (2014) assert that there are two main cognitive principles leveraged when using AR to learn for training, education, or gaining skills on-the-job:

- **Experiential learning** – the theory that humans learn by creating meaning from their own experiences;
- **Contextual learning** – to learn, humans must relate the concepts to something familiar, experience it through exploration, apply it to a real and relevant topic, cooperate and share the concept, and transfer their knowledge by applying it to a novel situation.

Bujak et al. (2013) meanwhile argue that AR improves learning through two main mechanisms:

- **Spatial and temporal contiguity** – putting related pieces of information either spatially or temporally close to one another to limit extraneous cognitive effort needed to link them – AR allows content to appear at the point of use and at the time of use;
- **Abstract-physical encoding** – when learning abstract concepts, AR can bridge the gap between symbolic and physical representations by merging or morphing them virtually.

Dunleavy and Dede (2014) reviewed the use of mobile AR in formal and informal learning settings, suggesting AR is primarily aligned with situated and constructivist learning theories. The Encyclopaedia of the Sciences of Learning (Gogus, 2012) defines constructivist learning as the theory that effective learning can only happen when learners interpret new information using their own contextual experiences to give them meaning. Situated learning theory meanwhile is the premise that learning occurs best through doing, rather than through passive receipt of knowledge (Aubrey and Riley, 2018).

AR takes advantage of both these methods of learning as it can provide knowledge within the domain it will be applied (i.e., the workplace). Alternatively, AR can be used to allow interaction with the virtual environment, rather than the real environment which enables ‘learning by doing’ by allowing learners to interact with virtual objects which can reduce some of the risks (financial, or safety related) associated with letting novices interact with physical work pieces or equipment.

2.5.2 Cognitive Load

As well as the mechanisms by which learning occurs, it is important to consider the issue of cognitive loading. Cognitive Load Theory is an approach to instructional design that considers how the structure and architecture of information affects the user's ability to process it (Sweller, 1988). The cognitive load of a task consists of three parts:

- **Intrinsic load** – the fundamental difficulty of the task
- **Extraneous load** – the way in which the information is presented
- **Germane load** – the way in which the individual uses their memory and intelligence to solve problems presented by intrinsic and extraneous loads

When delivering instructional or educational material there is a risk of cognitive overload – when the different aspects of cognitive load add up to overwhelm the user, often due to competing stimuli, and prevents task completion. Buchner et al. (2022) carried out a systematic review of cognitive load in AR studies, and concluded that AR task assistance and guided assembly showed no evidence of cognitive overload. In fact, they hypothesise that AR instructions reduce the impact of cognitive load through the split attention effect – by presenting instructions in the same spatial area as the task takes place, attention does not have to shift between the instructions and the task, thereby reducing extraneous load. However, they also note that while AR guidance generally resulted in lower or equal cognitive load compared to traditional methods, this effect is diminished when using mobile or wearable AR, as opposed to spatial methods.

2.6 AR and the Future Workforce

Whilst Section 2.4 demonstrates some of the latest literature in the field of AR for procedural instructions, thereby reducing the need for on-the-job training, this section explores how AR can deliver industrial training and education in new and innovative ways, to help build industrially relevant skills in the workforce of the future.

Please note: *some of the information contained in this section is based on a previously published paper*[2].

2.6.1 Drivers for Change

Hernandez-De-Menendez et al. (2020) predict that in the near future, rapid technological changes will lead to short product lifecycles in the manufacturing industry, meaning standard training for a single job will no longer be sufficient – instead, adaptability will be required and so cycle times for training must be reduced. This implies a need for training and education to be delivered in a more flexible way than current methods offer. Therefore, Hernandez-De-Menendez et al. propose the idea of Education 4.0. Much like Industry 4.0, it ushers in a new wave of technologies and approaches to learning, such as study tools that adapt to different learning styles, learning in different times and places, and a greater emphasis on practical activities and collaboration.

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[2] *SMITH, E., MCRAE, K., SEMPLE, G., WELSH, H., EVANS, D. & BLACKWELL, P. 2021. Enhancing Vocational Training in the Post-COVID Era through Mobile Mixed Reality. Sustainability, 13, 6144. Adapted with permission under the Creative Commons Attribution License.*

Another force at play was the **COVID-19** pandemic of 2020. In recent years, a trend towards project-based and active learning has seen success in engineering education (Graham and Crawley, 2010), however since 2020 this has been somewhat hampered by lockdowns and stay at home orders in place across much of the world. This only accelerates the need for alternative methods of delivering educational content. Internet-based leaning and development already exist in a variety of forms – e.g. **MOOCs (Massive Open Online Courses)**, **TORQUEs (Tiny, Open-with-Restrictions courses focused on Quality and Effectiveness)**, and Moodle (open source online learning platforms) courses at Zurich (Huba and Kozak, 2016). However, these have tended to be directed more toward academic and lecture-based education. Practical and vocational learning has suffered immensely in the wake of the COVID-19 pandemic, with enormous losses in terms of learning hours. AR may be able to help in two ways: by enhancing remote education, and by providing additional guidance on-the-job to reduce required experience before being able to operate independently.

A recent report by the Global Wind Energy Council predicts a workforce of over 77,000 will be required globally just to install the planned capacity of wind turbines between 2020 and 2024, and expresses concerns that a suitably qualified workforce may become the bottleneck for future installation targets (Global Wind Organisation, 2020). Delaying the training and qualification of new apprentices and students could seriously affect this goal, so it is important for the industry to come up with novel ways of delivering course content to make the training process more resilient to disruption going forwards.

Many of the more academic educational environments have been able to deploy teaching using video-conferencing software, pre-recorded content and online quizzes with some level of success. However, in recent years, a trend towards project-based and active learning has seen success in engineering education (Graham and Crawley, 2010). This has been significantly hampered by lockdowns and stay-at-home orders in place across much of the world.

Mixed reality (MR) technology meanwhile could provide a more interactive learning experience, using immersive visualizations for a more realistic replication of vocational learning. Unlike pure virtual reality (VR), which tends to require expensive custom-built kits, MR is very accessible to the remote learner, requiring as a minimum a smartphone or tablet and an internet connection. MR also has an advantage over VR in that it allows a view of the real world, which reduces the health and safety implications of virtual content that may occlude hazards in the users' environment.

Virtual learning techniques may never be able to fully replace in-person experiences, but they have the potential to reduce the number of hours required to physically access assets, which is a critical factor in enabling social distancing protocols. Reducing contact hours also has benefits for the post-COVID world, enabling more distance learning to take place. This is desirable for several reasons, such as reducing the impact of time-constrained equipment access. For example, in the offshore wind industry, it may be advantageous to have learners begin to familiarize themselves with some of the mechanical maintenance tasks, such as use of manual tightening and measuring tools, throughout their training period. However, physical access to a wind turbine is not allowed until the learner has completed a Working at Heights certification (Global Wind Organisation, 2019). Given the predicted skills shortage mentioned earlier, anything that can reduce bottlenecks in the training process would be beneficial. Therefore, the flexibility of a digital learning application could allow users to start practicing at an earlier stage of their studies and keep up the practice as needed to build confidence and competence at the task. As Marienko et al. (2020) found, AR and VR can be particularly useful in replicating future work environments, ultimately leading to improved workplace productivity.

Further, it allows users to practice tasks as frequently as they like and at a time that suits them, which may open up more opportunities for those studying part-time alongside a job or managing additional unpaid responsibilities that preclude them from learning in the standard 9am–5pm pattern. This paves the way for a more diverse workforce. Add to this the existing engineering skills gap in the UK - McKinsey estimate that around 94% of today's UK workers across all sectors will lack the skills to perform well at their current job by 2030 (Allas et al., 2020) — and it is clear that the UK can ill afford to fall behind in training and upskilling the next generation.

This is particularly true if Gorecky et al.'s prediction for the future of manufacturing comes true, in which virtual training is delivered to the shop floor via mobile devices linked to a semantic knowledge platform and accessed via the Web (Gorecky et al., 2013). While just a vision at present, this shows how MR and Industry 4.0 technologies are increasingly envisaged as becoming part of the workplace. A case study from BMW shows that this prediction may not be far off, as the authors showcased an example where head-worn AR was used to train associates on the assembly line (Morkos et al., 2012). As well as saving on the cost of hiring trainers, they also claimed that trainees benefitted from the flexibility to learn at their own pace, though no numerical data were provided to support this suggestion.

2.6.2 AR in Education and Learning

In higher education settings, AR has been used to teach mechatronics students the basic principles of operating milling and lathe machines (Monroy Reyes et al., 2016). The app used marker-based AR delivered via smart and touchpad control. A mixture of 3D models, videos and annotated instructions were used. Participants answered 10 questions for system acceptance and performance to judge the success of the system; however, the researchers did not directly measure performance, for example, in terms of speed or accuracy. Similarly, Bloxham (2014) found that AR is particularly useful for vocational degree courses (in this case, wearable crib sheets for automotive technology), where it can provide virtual access to practical content and learning that may otherwise be limited if only the physical world is used. A study at the **National University for Distance Learning (UNED)** in Spain compared AR mobile apps with a video for learning about occupational health and safety (Cubillo et al., 2015). Students in the AR condition were more likely to review the content again at home and scored significantly higher than those who had access to the video content. Students reported the AR as being more interesting, easier to access and use, and more enjoyable to use to share learning with fellow students (an example of contextual learning). This suggests that MR tools can indeed enhance the practical aspects of a vocational education and may be used alongside physical practice to achieve learning objectives. Pan et al. (2017) used mobile AR to superimpose 3D models and sectional views to aid manufacturing design students. They reported a perceived improvement in learning efficiency, while noting that an AR solution such as this also reduces teaching workload.

A comprehensive meta-analysis of 87 research articles describing AR applications used for education and learning was carried out (Santos et al., 2014). It was determined that AR interventions have a moderate positive influence on learning (mean **effect size** of 0.56). However, this is not as clear-cut as it first may seem. The measures of learning are not consistent across the studies, and therefore Santos et al. make recommendations on best practice for data collection, including:

- Learning effect should always be measured by comparison of an experimental group to a control group;
- Extraneous variables must be carefully controlled;
- Both mean and standard deviation should always be reported to allow comparison of the relative effect sizes of different interventions.

Prior research in the field of AR education also supports the concept of MR as a training tool, In the Philippines, portable AR guidance for vocational and technical training was trialled in K-12 education (5–17 year olds) (Dayagdag et al., 2019). Implemented via a head-worn AR display with a wristband for gesture control of the AR content, the app delivered training in four stages—Demonstration, Simulation, Application and Evaluation. Real-time video assistance with a remote expert was also available in the case of any issues. The researchers reported it positively; however, no data were presented to support its success and it should be noted that head-worn display technology remains costly and may not be accessible to most school pupils.

Ibáñez and Delgado-Kloos (2018) reviewed the use of AR in **STEM (Science, Technology, Engineering, and Mathematics)** -based learning. They found that while life sciences most commonly used location-based content for learning outside of class (an example of contextual learning), physical sciences typically used AR within the classroom to view 3D and contextualised information more clearly, which is aligned with the idea of experiential learning.

This review also highlighted inconsistencies in data collection between AR learning studies, citing common measures to be usability, cognitive load, and (most frequently) cognitive ability. However, these metrics were often measured using ad-hoc questionnaires, limiting the extent to which meaningful comparisons can be made between studies. Additionally, it was rare to explore whether learning goals were met (particularly important in education-based applications), and cognition was only measured at a low level, and over short periods.

In terms of how successful AR is in education and training settings, a review by Chang et al. (2016) found that Taiwanese schools have used AR to great effect in the form of an interactive mobile app about plant growth compared to a digital video conveying the same knowledge. Though both learning techniques resulted in a good level of effectiveness immediately after learning, the AR condition was shown to be more effective in a delayed-test questionnaire, suggesting AR helps learning retention.

Marienko et al. (2020) suggest that one of the main benefits of AR and VR learning over traditional methods is the ability to personalise learning experiences to individuals to improve efficiency and effectiveness of their learning. In particular, they recommend the use of AR and VR to replicate future work environments, which leads to improved productivity in the workplace when compared to traditional classroom only teaching.

2.7 Discussion

Following a brief history of visualisation technologies (Section 2.2), AR was defined as those technologies that visually combined virtual information with the real environment (Section 2.3). There are a variety of different methods of achieving this - whether via optical combination, video mixing, wearable devices, or handheld ones – and this research aims to leverage these technologies to facilitate better performance in industrial assembly and maintenance tasks. This was achieved through several cognitive mechanisms that aid understanding of information delivered via AR.

In Section 2.4, literature regarding applications of AR in assembly and maintenance, especially guided maintenance (i.e., direct delivery of instructions) was critically surveyed. While many of these works found improvements in accuracy, task time, and cognitive effort, especially in complex tasks, there was a lot of variation within those results and some studies even showed a negative impact on performance. There was little research to suggest which specific features or qualities of the AR apps was causing these differences in performance level.

Another key factor in success of an AR instruction app is user acceptance – without buy in from those using the technology daily, it is difficult for a new technology to succeed. The studies observed in Section 2.4.2 suggest that workers are generally positive towards the technology and are even willing to tolerate minor technical issues if AR overall makes their job easier. There were few studies regarding applications of AR in a wind turbine or similar extreme environments (Sections 2.4.3 - 2.4.4). The ones that do exist, show promise for the technology but often lacked statistical rigor or comparison to a different method of instruction delivery to demonstrate how effective it was.

Studies in Section 2.5 suggest that showing information in the context of use reduces the cognitive effort required to interpret it and enables learners to better apply abstract concepts to the real world. Additionally, the use of MR technology enables 'learning by doing' by allowing users to practice and interact with virtual assets.

Several studies that used AR for training and learning (as opposed to on-the-job guidance) were presented in Section 2.6. Driven by an increased emphasis on online learning in the wake of the COVID-19 pandemic, and a recent trend toward project-based learning, there is a need for remote learning methods to replicate the experience of practical experiences. This new paradigm for learning has yet to be extensively tapped in the field of vocational learning. However, in studies that make use of AR in classroom learning, it was shown to have an overall positive effect on learning. Despite promising research in the field of AR for learning and education, there are still questions over whether high-level cognition occurs during AR-based learning, and whether the improved learning effect is still true in the long term or if there is a novelty effect at play.

2.8 Aims and Objectives

From the work outlined in Section 2.7, it is evident that there is a gap in the research for high quality experimental studies that explore the different factors of IAR app design that affect user performance in assembly and maintenance tasks.

Robust statistical analysis should be carried out to ensure results are indeed significant, and performance should not just be measured by process output, but also in terms of user acceptance metrics, as technology adoption will surely fail if those who are to use the devices dislike them.

Novelty and experience with the technology may affect both user acceptance and other performance factors, so this is also a possible area for further investigation.

There is also clear scope for exploration of how AR and MR techniques can be used in engineering education to better train the workforce of the future, either through on-the-job guidance or by virtually supplementing classroom learning.

Therefore, the aim of the research detailed in this thesis is to investigate how Augmented Reality (AR) technology can be effectively deployed in manufacturing and engineering to improve performance, based on knowledge from the existing literature base, opinions of industry experts, and the results of experiments to determine the optimum settings for effective presentation of instructions and other information. At all stages, data will be analysed statistically to ensure results are robust and statistically significant.

This aim will be achieved by setting the following objectives:

Research Objective 1 To develop a flexible cross platform AR research tool which can operate using a variety of user interaction modes (Chapter 5)

Research Objective 2 To determine the most effective way of presenting AR procedural instructions for a simulated industrial task (Chapter 5 and 6)

Research Objective 3 To investigate the effect of learning and novelty on performance when following AR instructions (Chapter 7)

Research Objective 4 To explore novel methods of incorporating MR technologies into engineering training and education (Chapter 8 and 9)

3 Research Design

3.1 Introduction

It is important to specify and clearly define a research design to ensure the logic underlying the research is robust and systematic. The philosophy underlying the research as a whole is discussed in Section 3.2. Then, appropriate research strategies for this philosophy were considered in Section 3.2. Finally, Section 3.3 outlines specific strategies, their advantages and disadvantages, and examine how they were used to meet the research objectives.

The research strategies defined here were important in facilitating the work of Chapter 4, in which statistical methods appropriate to the study design were devised and experimental metrics were identified to enable the experimental work discussed in Chapters 5 - 9.

3.2 Research Philosophy

The research philosophy concerns the basic methodological assumptions that underpin the research strategy. Different research philosophies can be characterised by the following aspects (Alharahsheh and Pius, 2020):

- **Ontology** - the study of the nature of reality and being
- **Epistemology** - the critical study of the nature of human knowledge
- **Methodology** - general research strategy
- **Methods** - collection and analysis of data to develop new knowledge

Positivism assumes that reality can be observed and described in an objective manner, and that different phenomena can be isolated and repeated (Levin, 1994). Positivist approaches typically take an objective view of ontology, and in terms of epistemology tends to focus only on phenomena that can be directly observed and measured. Positivist methodology therefore tends to favour quantitative research, generally choosing methods that involve manipulation of variables to identify relationships in the observed world (Saunders et al., 2009).

In contrast, **Interpretivism** states that subjective interpretation of reality is the only way to fully understand phenomena (Saunders et al., 2009). It acknowledges the fact that researchers affect the world as they study it and that to view the world in a purely objective manner would be to dismiss a lot of important detail about how humans experience the world. Thus, Interpretivists often favour qualitative methods (Johannesson and Perjons, 2014).

Table 3.1 – Summary of main research strategies (Johannesson and Perjons, 2014)

Strategy	Purposes	Key concepts	Key activities	Forms	Major concerns
Experiment	Investigate cause and effect relationships	Hypothesis Dependent variable Independent variable	Control factors that may influence the dependent variable	Laboratory experiments Field experiments	Weak external validity for laboratory experiments Weak internal validity for field experiments
Survey	Investigate some aspects of a phenomenon to get an overview	Sample Representative sample Exploratory sample	Sampling (random, purposive, and convenience)	Interview survey Observational survey Document survey	Lack of depth Limitation to measurable aspects Lack of theoretical grounding
Case study	Investigate in depth a phenomenon with a well-defined boundary	Case/instance Natural setting Holistic view	Multisource data collection Triangulation	Exploratory case study Descriptive case study Explanatory case study	Weak generalisability
Ethnography	Investigate cultural practices and social interaction	Culture Empathy Researcher as active participant	Field work Capture social meanings	Holistic study Semiotic study Critical study	Reflexivity A-theoretical storytelling Ethical dilemmas
Grounded theory	Develop concepts and theories through analysing empirical data	Categories and codes Open-mindedness Theory and concept generation Theoretical saturation	Theoretical sampling Coding (open, axial, and selective)	Positivist Interpretivist Constructivist	Reflexivity Lack of context
Action research	Produce useful knowledge by addressing practical problems in real-world settings	Active practitioner participation Change in practice Action and research outcomes	Cyclical process Diagnosis Planning Intervention Evaluation Reflection	Technical action research Practical action research Emancipatory action research	Weak generalisability Lack of impartiality
Phenom-enology	Describe and understand the lived experience of people	Lived experience Reflectivity	Unstructured interviews		Lack of rigour

The research presented here focused on not only technology, but also the interaction between human beings and AR technology. Therefore, while some aspects of Positivism such as the isolation and manipulation of variables to study relationships were taken, a purely Positivist approach was not appropriate. Some aspects of Interpretivist philosophy to understand subjective factors in performance and acceptance of technology were adopted too, leading to a mixed methods approach. This philosophy is known as **Pragmatism**, in which both subjective and objective points of view are considered to answer research questions by any means necessary (Creswell and Creswell, 2017).

3.3 Research Strategies

Once a general philosophy and approach to research was selected, specific strategies to answer the research objectives were chosen. There are many possible research strategies in existence, some of the key ones are outlined in Table 3.1 (pg. 56). This research focussed on the impact of instruction delivery and their effect on user performance. Performance has both objective and subjective aspects (see Section 4.2), so the research studies were designed to acknowledge both these important characteristics. This involved experiments to capture objective data about user output, but also surveys and case studies to gain a broader understanding of user experience with these technologies.

In the following sections (3.3.1 - 3.3.2), specific research strategies are discussed in terms of their rationale and how they contribute to achieving the overall research aims laid out in Chapter 2.

3.3.1 Survey

Surveys were utilised several times during this research. Firstly to capture the needs of the industry for identifying experimental metrics in Section 4.2.2. They were also used as part of a mixed methods approach to data collection in experiments.

Internet-based surveys were selected in order to more easily reach a wide audience, at low cost (both time and money), and with a shorter response time compared to postal surveys (Andrews et al., 2007). Respondents were contacted via email, which directed them to access a web-based survey where they could answer questions at their convenience. Another advantage of online surveys is that data is stored to a digital database automatically, reducing the risk of transcription errors compared to paper-based surveys. The surveys were created in *Qualtrics* online questionnaire software (Qualtrics, 2018), which allows for easy distribution to respondents, and supports multiple platforms and browser types to suit the respondents' preferences.

A mixture of closed-ended and open-ended questions were used to gather both quantitative and qualitative feedback at all stages of research, including:

- **Multiple choice** – to collect quantitative, categorical data such as user demographic, consent to data processing, binary agree/disagree statements
- **Likert scales** – to collect qualitative data on user experience, preferences etc. by comparing to a standardised ordinal scale
- **Freeform response** – to collect longer, more discursive information based on user opinions, or data for which likely categories are not known beforehand (e.g. occupation)

To ensure respondents could answer questions freely and without judgment, pseudo-anonymous Participant IDs were used to link survey responses to experimental data without identifying anyone personally.

3.3.2 Experiments

To achieve each of the objectives laid out in Section 2.8, a series of experiments were designed. Unlike surveys, experimental work provides to opportunity to deliberately manipulate variables and directly observe their effect on key performance indicators, however the research cost (both time and resource) is significantly higher. Additionally, there is a higher barrier to entry for participants, in terms of both time and effort, which can make recruitment more difficult and therefore puts a practical limitation on sample sizes.

The experiments in Chapters 5 and 6 were carried out in controlled ‘lab’ conditions on the university campus. This has the advantage of low experimental cost, and an easily accessible pool of participants, which enabled a higher sample size, therefore making it easier to detect significant differences in the data. In Chapters 7 and 8, experiments were carried out remotely (discussed further in 4.6), which permitted less control and direct observation, but still enabled large sample sizes due to the low barrier of entry for participants.

The study in Chapter 9 was carried out in a more industrial setting. This was far more representative of the end use case and therefore was important for understanding practical considerations of how AR may be implemented in the engineering industry.

3.4 Summary

In this section, common research philosophies were discussed, before selecting the approach for this research: Pragmatism. The Pragmatic research philosophy allows for consideration of both subjective and objective measures, which are critical to research that examines the interaction between humans and technology, such as the studies presented in this thesis (Section 3.2). Pragmatism typically utilises mixed research methods to achieve its goals, and in this case, the specific research strategies of surveys and experiments were both used to achieve the research objectives (Sections 3.3). Since the underlying design considerations of the research are now defined, Chapter 4 will describe specific decisions about research methods, procedures, and analyses chosen for the studies presented in this thesis.

4 Research Methodology

4.1 Introduction

While Chapter 3 discussed the theoretical underpinnings for the research presented here, this chapter discusses the specific methods and procedures used to obtain research data and synthesise it into knowledge in order to meet the research objectives of Section 2.8.

In order to design studies that can provide insight into the influence of AR on maintenance task performance, it is necessary to identify key variables involved. Therefore, Section 4.2 explores which variables were to be investigated during the research, as well as defining methods of data collection. Similarly, in Section 4.3, previous literature on the topic of industrial AR was examined in order to calculate the minimum recommended sample size for Studies 1-3.

As discussed in Section 2.7, a key aspect of experimental work is the use of robust statistical investigation of experimental data, to look for meaningful results. In Section 4.5, three different methods for analysing the data are discussed, with a focus on identifying significant differences between different experimental conditions, according to the structure and nature of the data collected.

Finally, a number of changes to the planned experimental methods were necessary due to restrictions on social contact during the COVID-19 pandemic, this of course had repercussions in terms of the limitations of the research that is discussed in Section 4.6. This chapter serves as a general background for the studies carried out in Chapters 5 - 9; however, specific research methods to meet each objective are discussed in more depth in each of those chapters respectively.

4.2 Measures of Performance

Before beginning any kind of study, it was essential to define the key performance measures to allow the design of appropriate experiments. These dependent variables were identified firstly through a review of popular studies in the literature, to ensure that results can be compared to other studies in the field (Section 4.2), and secondly by using a survey of industry professionals to gauge the priorities and challenges facing those working in offshore wind (Section 4.2.2).

4.2.1 Common Metrics in Literature

These experiments build on the field of **Human-Computer Interaction (HCI)** and focus primarily on user interaction methods, and instruction display. HCI refers to "the study of the way in which computer technology influences human work and activities" (Dix, 2009). Techniques and common metrics from this field can be applied to the work presented in this thesis, to examine the influence of AR on maintenance work.

To identify common metrics in the literature, 16 popular papers about AR usability studies (not necessarily in the field of assembly and maintenance) were explored and the performance measures used in each were recorded. These were collated, and the most frequently occurring ones were noted - Table 4.1 (pg. 65) shows the top results, alongside suggestions of how they can be implemented. Data collection methods selected for use in the final study are highlighted in bold in the final column of the table.

Table 4.1 - Top performance measures in literature (full results in Appendix A**)**

Performance Measure	Frequency	Data Collection Method
TCT	6	**Measure**
Easy to learn	6	Likert/**QUIS**/**SUS**
Ease of use	6	Likert/**SUS**/**TAM**
Mental Demand	6	**TLX**/**SMEQ**/Likert
Performance	5	Measure/**TLX**/Likert
Intuitiveness	5	Likert/**ranking**
Physical Demand	4	**TLX**
Temporal Demand	4	**TLX**
Effort	4	**TLX**
Frustration	4	**TLX**
Accuracy	4	Likert/**ER**
Open	4	**Freeform comments**
ER	4	**Measure**
Would like to use frequently	3	**SUS**
Complexity	3	**SUS**
Requires technical support	3	**SUS**
Functions well integrated	3	**SUS**
Inconsistency	3	**SUS**
Cumbersome	3	**SUS**
Learning curve	3	**SUS**

Please note: *QUIS = Questionnaire for User Interface Satisfaction, SUS = System Usability Scale, TAM = Technology Acceptance Model, TLX = NASA-TLX or Task Load Index, SMEQ = Social Media Engagement Questionnaire, ER = Error Rate. Please refer to the List of Abbreviations and Acronyms on page xxiii for further detail.*

4.2.2 Challenges and Opportunities in Industry

Increasingly, the engineering community is beginning to recognise the potential of AR in challenging industrial environments as it provides a novel and intuitive way to access and interpret information without distracting the user from their task. However, adoption has been slow and many organisations are struggling to understand how AR can apply to their work specifically and how they can benefit from it (Masood and Egger, 2020). Therefore, a survey of the wind industry and maintenance professionals was issued, with the aim of better understanding the current state of Augmented Reality technology in the industry, as well as capturing key challenges and opportunities for improvement in the field of maintenance. In particular, survey data assisted in understanding the most important factors as a basis for planning later experimental work.

Forty-eight participants responded to the call, though only 25 completed 100% of the survey, the rest recorded partial responses. Full results tables and a copy of the survey can be found in Appendix B. Chart 4.1 (pg. 67) shows that most respondents worked in the field of either onshore of offshore wind, while others worked in other forms of renewables, industrial maintenance, space, education, and investment. Please note respondents were able to select more than one category, so percentages do not add up to 100%.

The survey was shared amongst existing contacts in the field of offshore wind and industrial maintenance. It was also shared on social media, with messages asking readers to complete and share the survey with anyone they felt had relevant knowledge and experience.

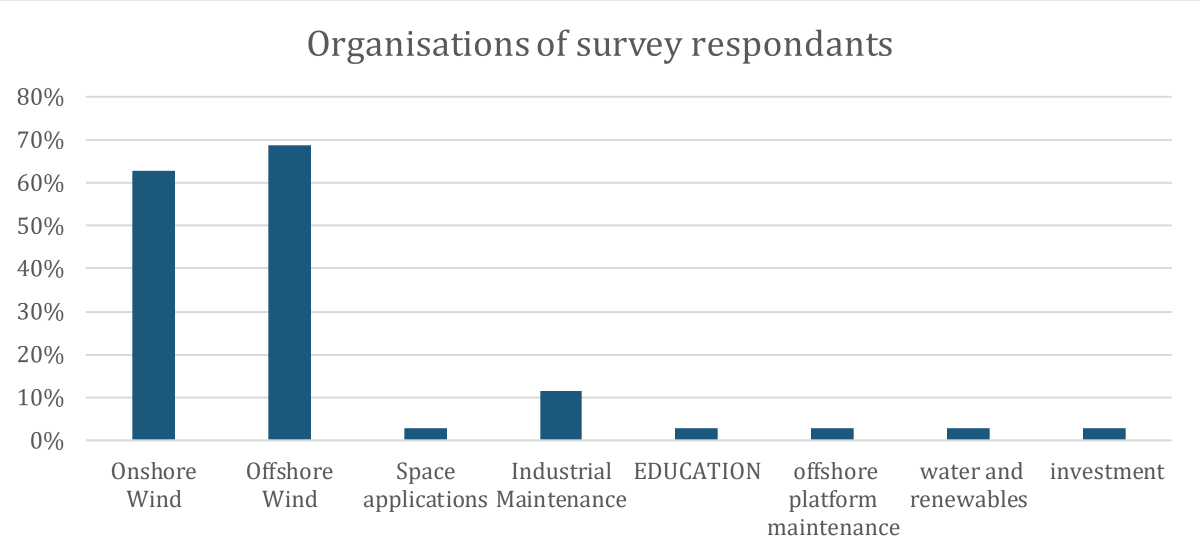


Chart 4.1 – Survey responses to the question 'Which area does your organisation mainly operate in?'

The roles of the respondents were diverse, ranging from research roles to directors. The most common occupation was an engineer of some variety, consisting 43% of those who answered that question.

57% of respondents said they did not believe their organisations currently used AR, citing lack of knowledge about AR (30%), implementation costs (22%), unclear benefits (19%), and site-specific restrictions (5%) as the main reasons for this (Chart 4.2, pg. 67).

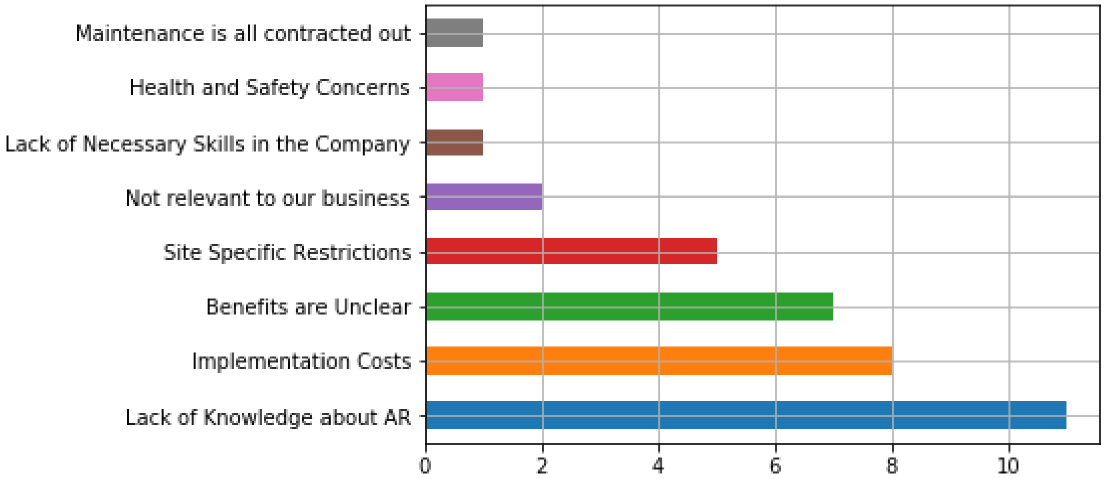


Chart 4.2 - Survey responses to the question 'Please select the main reasons you think your organisation does not currently use Augmented Reality?'

All participants then rated some potential limitations of AR technology based on perceived importance, from not at all (1) to extremely important (5). The top three rated concerns were Implementation Costs (with an average score of 4.375), Physical Safety of Workers (4.333), and Data Protection and Cybersecurity (4.28) (Chart 4.3).

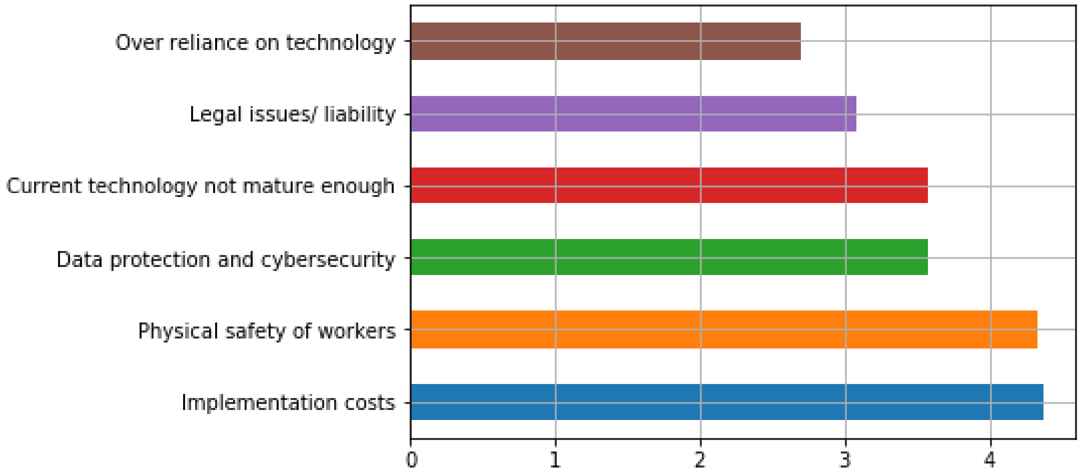


Chart 4.3 - Survey responses to the question 'Listed are some possible concerns or limitations of implementing Augmented Reality. Please rate how important you consider them to be in the context of your work?'

On the same scale, participants were asked to rate the importance of some potential benefits of AR. Not all participants were experts in AR, so a brief description of what the technology involved was provided in the question text. The top three rated benefits were Reduced Error Rate (average score of 4.478), Improved Task Completion Time (4.375), and Reduced Time Locating Items (4.333) as shown in Chart 4.4 (pg. 69).

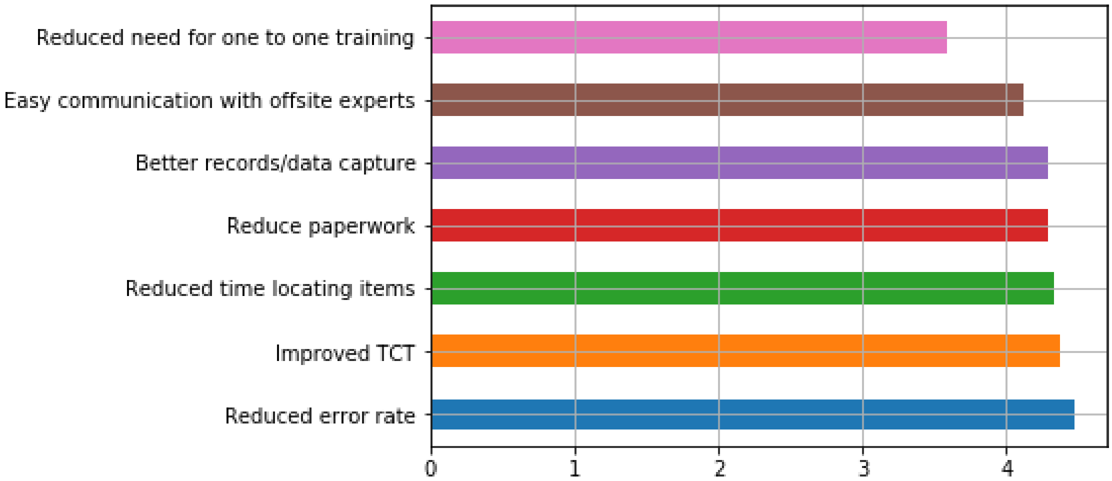


Chart 4.4 - Survey responses to the question 'Listed are some likely benefits of using AR to guide industrial maintenance. Rate how important you think these improvements would be.'

Full results, a copy of the survey and data protection statements are given in Appendix B (pg. 276).

4.2.3 Implementation of Variables

Summarising the outcome of 4.2.1 and 4.2.2 suggested the research should focus on the following four dependent variables (Table 4.2):

Table 4.2 – Description and shorthand for dependent variables

Task Completion Time	Time in seconds from start of task to completion	**TCT**
Error Rate	Number of errors (whether corrected or uncorrected) made during the task	**ER**
Cognitive Load	Mental effort required to complete the task, measured using the **NASA-TLX** scale (Hart and Staveland, 1988)	**TLX**
System Usability	Perceived ease of use of the system, measured using the System Usability Scale (Brooke, 1996)	**SUS**

Table 4.3 (pg. 70) summarises the independent variables considered during this study, and how they were implemented. Detailed explanation of how this was included in the application design can be found in Section 5.2.1.

Table 4.3 - Variables and Experimental Implementation

Factor	***Level***	**Implementation**
Device Type	*Mobile*	Content visualised using a mobile phone - **HTML/CSS** and JS front end, Node.js backend
	HMD	Content visualised using Microsoft HoloLens - HTML/CSS and JS front end, Node.js backend
Interaction Method	*Native*	Users interact with content using the device's native interaction method to navigate instructions i.e. touch screen for mobile, hand gestures for HoloLens
	Voice	Users interact with content using voice commands to navigate instructions
Display Mode	*CAD*	Instructions are conveyed to the user in the form of **CAD** models showing where actions should be performed
	Text Annotation	Instructions are conveyed to the user by concise written instructions, linked to the relevant location by an arrow
	Video	Instructions are conveyed to the user by videos of the action to be performed, projected over the relevant location

The cognitive load was measured using the **NASA-TLX** questionnaire (Hart and Staveland, 1988), now considered a standard in HCI research (Hart, 2006). The scale asks users to rate the mental, physical, and temporal demand of the task they completed, as well as their performance, the effort required and frustration whilst performing the task. The unweighted version of the **Task Load Index (TLX)** scale simply takes an average of the values provided, while the weighted version also asks the users to choose which of the above factors was more important. A review of nearly 20 years' worth of research using the TLX scale suggests that weighting does not significantly affect the outcome (Hart, 2006); therefore, the unweighted version of the scale was used in all following experiments, for the sake of brevity.

Error Rate (ER) and **Task Completion Time (TCT)** were rated as very important factors in an AR system, as was reduced time locating items, therefore Error Rate (as a proxy for right-first-time performance) and task completion time formed part of the definition of good performance, and were included as dependent variables in the experiments.

Finally, the **System Usability Scale (SUS)** score was measured to understand the perceived difficulty of using the technology.

All 4 of these dependent variables are summarised in Table 4.4.

Table 4.4 – Dependent variables to be measured during experiments and the source from which the data was gathered

Dependent Variable	Definition	Operationalization	Data Source
Task completion	Time taken to fully complete a task or subtask	Time elapsed between the start and end of task/subtask	Timer built into the app
Error rate	Number of errors made during task completion	Error count (corrected + uncorrected)	Observation of task
Cognitive Load	Mental effort required to complete a task(Hart, 2006)	Unweighted NASA-TLX Score	Post-study questionnaire
Usability	Inclination or aversion felt towards the technology (Brooke, 1996)	System Usability Scale	Post-study questionnaire

4.3 Sample Sizes

In the literature reviewed in Chapter 2, many studies used similar measures of performance when using AR in industrial settings (Section 2.8), allowing results to be compared across studies. Therefore, a meta-analysis was conducted to determine typical effect sizes in the field of AR guided assembly user studies, thus allowing the calculation of required sample sizes for original research carried out in Chapter 6 and 8. It is important to calculate minimum sample sizes when planning experimental work, to ensure a good level of confidence that differences in the data will be detected where they truly exist.

SCOPUS, Engineering Village, and IEEE Xplore databases were searched using the terms:

("Augmented Reality" OR "Mixed Reality") AND ("Maintenance" OR "Repair")

Search results were also filtered such that only papers published after 2013 were considered. This is because Industry 4.0 principles began to emerge in this period, as shown in Chart 4.5.

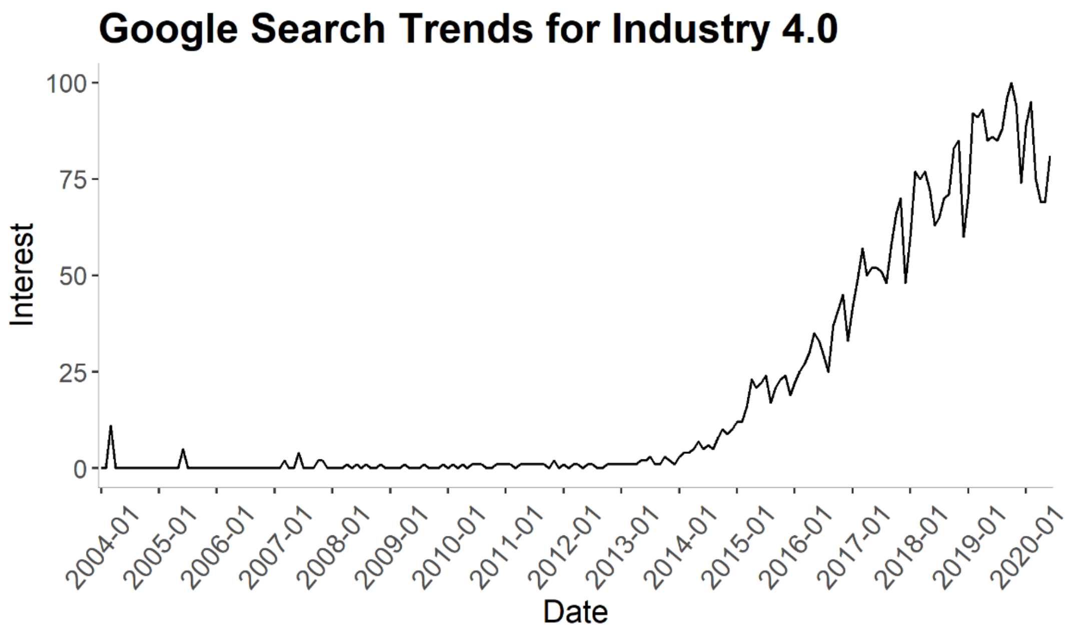


Chart 4.5 – Google search trends for the term "Industry 4.0" from 2004

The search resulted in 1107 records, 599 of which were unique. These records were then parsed to see if they matched the inclusion/exclusion criteria through three layers of screening – title, abstract, and finally full text. Inclusion/exclusion criteria in were identified using a **Population, Intervention, Comparison, Outcomes, Context (PICOC)** framework (Booth et al., 2016), to identify papers that described an industrial application of AR instructions, with a comparison of performance against traditional instruction methods, and specific measurable metrics by which performance was judged (Table 4.5).

Table 4.5 - PICOC Framework for selecting papers to include in systematic review

	Inclusion	**Exclusion**
Population	Industrial maintenance task Human Operators Application	Training applications only Medical application Robotic control/teleoperation Describes technical development
Intervention	Utilisation of AR	Utilisation only of VR
Comparison	Paper manuals Static PC-based instructions	
Outcomes	Time to complete operation Number of errors User experience	Improved algorithms Image recognition Time to develop the application
Context	Industrial environments	Consumer environment

The number of records excluded at each stage are shown in Table 4.6 (pg. 74), with thirteen unique records matching all the specified criteria.

Table 4.6 - Included/excluded papers at each stage of literature review

Original	**1107**
Duplicates	508
Title Screening	**599**
Not maintenance	39
Not AR	10
Medical/Biological	52
Robotic control/tele-operation	16
Consumer use	24
Specific technical development	186
Education	29
Cultural/Heritage	21
Abstract Screening	
Not maintenance	11
Not AR	5
Medical/Biological	1
Robotic control/tele-operation	3
Consumer application	4
Specific technical development	50
Education	3
Full-Text Screening	
Non-English language	3
No data presented	4
Assisted maintenance	8
No comparison to traditional instructions	117
Records remaining:	**13**

Thirteen unique records were identified which detailed user studies of AR in industrial maintenance, five of which provided enough data to calculate an estimate of effect size. These are shown in Table 4.7 (pg. 75). The last column (*Effect Size (Cohen)*) shows the effect size, calculated according to Cohen's methodology (Cohen, 2013) where **Cohen's D** is a measure of effect size, calculated as a standardized mean as shown in Equation 1.

Equation 1 - Cohen's D (Cohen, 2013)

$$Effect\ size, \partial = \frac{\mu_2 - \mu_1}{\sigma}$$

where μ_i is the population mean, and σ is the population variance.

Table 4.7 - Papers for inclusion in meta-analysis and effect size presented

Author	Title	Conditions	Effect Size (Cohen)
(Lamberti et al., 2014)	Challenges, Opportunities, and Future Trends of Emerging Techniques for Augmented Reality-Based Maintenance	AR v Paper AR v Paper (novices)	-2.854 -1.223
(Ramakrishna et al., 2017)	An AR Inspection Framework: Feasibility Study with Multiple AR Devices		
(Sanna et al., 2015)	Using handheld devices to support augmented reality-based maintenance and assembly tasks	AR v Paper	-0.2854
(Zaldivar-Colado et al.)	A mixed reality for virtual assembly	MR v Paper	2.223
(Havard et al., 2016)	Augmented industrial maintenance (AIM): A case study for evaluating and comparing with paper and video media supports	AR Glasses v Paper AR Tablet v Paper	-0.2635 -0.05720
(Uva et al., 2017)	Evaluating the effectiveness of spatial augmented reality in smart manufacturing: a solution for manual working stations		
(Gheisari et al., 2014)	Locating building components in a facility using augmented reality vs. paper-based methods: A user-centred experimental comparison	AR v Paper	
(Suarez-Warden et al., 2015)	Assembly Operations Aided by Augmented Reality: An Endeavour toward a Comparative Analysis		
(Fiorentino et al., 2014)	Augmented reality on large screen for interactive maintenance instructions		
(Perdikakis et al., 2015)	Introducing Augmented Reality in Next Generation Industrial Learning Tools: A Case Study on Electric and Hybrid Vehicles		
(Zhu et al., 2013)	An authorable context-aware augmented reality system to assist the maintenance technicians		
(Gavish et al., 2015)	Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks	AR v Demo	-0.08687
(Rios et al., 2013)	A mobile solution to enhance training and execution of troubleshooting techniques of the engine air bleed system on Boeing 737		

According to Cohen, small (0.2), medium (0.5) and large (0.8) effect sizes can be used as guidelines. Plotting the results of the meta-analysis against Cohen's standard estimates, Chart 4.6 (pg. 77) shows that the typical (mean) effect size based on these studies is close to Cohen's estimate for a large effect size of 0.8. Therefore, 0.8 will be used in future calculations of experimental power and sample size.

For an experiment to be useful, it needs to have sufficient **statistical power** to allow reasonable confidence that significant differences in the data will be detected if they exist. Typically, the minimum accepted power level is 80% (Hair et al., 1998) - i.e., 80% of the times when a genuine relationship exists between data, it will be correctly identified.

Power is calculated based on sample size, **effect size**, **significance level** and the number of independent variables. Significance level refers to the highest risk of **Type I error** (incorrectly identifying a relationship where none exists) accepted as a significant result – a minimum level of 90% was considered acceptable when exploring the possible ways to achieve 80% power. Sample size should be kept as small as possible, to reduce experimental cost – in this case, the sample size is the number of participants in each different treatment, so the number of levels in each treatment affects the sample size. The number of independent variables was fixed – for initial power calculations there were three independent variables each with up to three levels as shown in Table 4.8 (pg. 76).

Table 4.8 - Factors and levels considered in Phase 1 of experiments

Independent Variables (Factors)		**0**	**1**	**2**
A	Device Type	Mobile	HMD	
B	Interaction Method	Native	Voice	
C	Display Mode	CAD Models	Text Annotations	In-situ Videos

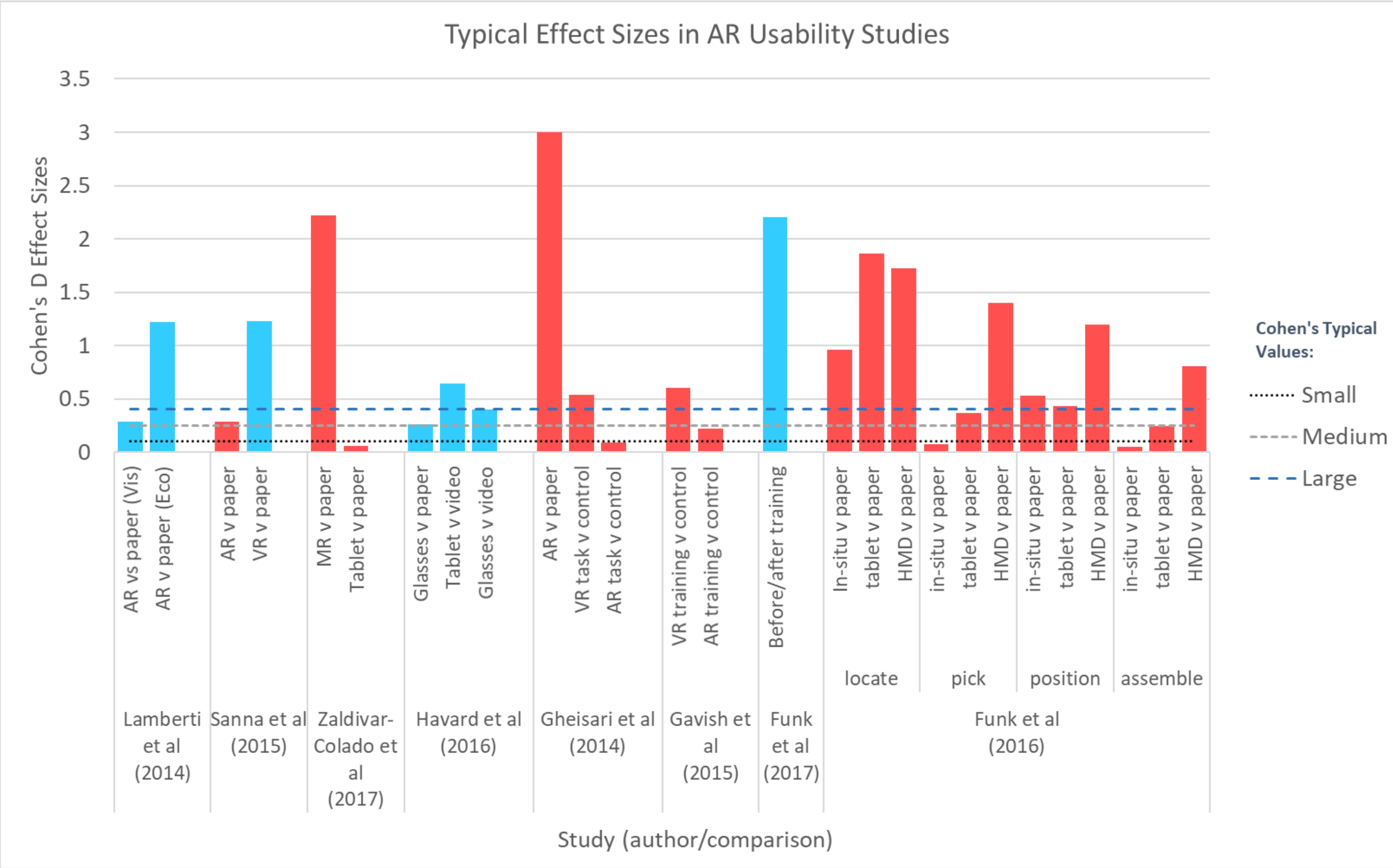


Chart 4.6 - Effect sizes in usability studies

Using the *'pwr'* package in R (Champely, 2018) sample size of 24 (n = 24) gives sufficient power to detect differences in both the main effects of each factor (device, interaction, display) as well as all interaction effects, so the minimum sample size for the experiments in Chapter 6 is 24 participants. There are two factors with 2 levels, and one with 3 levels, giving a total of 12 different conditions considered in the experiment, so a sample size of n=24 gives 2 participants in each condition (Table 4.9).

Table 4.9 – Sample size based on factors and levels

Factors	**Levels**	**Min. Sample Required**
Device Type	2	$2^2 3^1 \times 2 = 24$
Interaction Method	2	**Preferred Sample**
Display Mode	3	$2^2 3^1 \times 4 = 48$

In practice, a sample size of 48 (4 per condition) was used to provide additional capacity to detect small differences in performance.

4.4 Experiments

To achieve Research Objectives 1 - 4, a series of experiments were devised. The following section outlines the aims, key variables, and basic procedure for each study. Experimental work is broken down across five chapters, each of which serves a different purpose and uses a different sample task to replicate industrial tasks. A unique sample of participants were used for each of the trials. Ethical approval for these studies was considered, and the Ethics Checklist is included in Appendix C.2.

4.4.1 Trial 0: Preliminary Study

Research Objective 1 - To develop a flexible cross platform AR research tool which can operate using a variety of user interaction modes (Chapter 5)

To enable later research studies, a flexible AR application was developed to deliver manufacturing work instructions in which a range of **User Experience (UX)** factors could be varied without impacting on the overall look and feel of the application. A preliminary study was then carried out, using this application and a short assembly task to gain initial user feedback on the application, and to identify any potential issues with either the application or the experimental design.

Some studies would suggest using a Wizard of Oz approach to this kind of experiment – i.e., instead of the software recognising the command; the person carrying out the research watches or listens out for it and manually triggers the next step of the software. The benefit of this approach is that it means performance is independent of software quirks and issues, and reduces time spent developing intermediate stage software. This approach was not used here because this research focusses on industrial applications of existing technologies, so it was desirable to emulate real-world conditions as closely as possible, including the fact that users had to perform the commands accurately in order to get a response from the AR system. Therefore, an actual working app was created in order to deliver AR instructions and capture key research data (Section 5.2.1), as per Research Objective 1.

Because of this, it was preferred to test the app and associated research methods with a small-scale experiment before proceeding to more substantive experiments. For that reason, Chapter 5 presents a preliminary study, Trial 0, a simplified version of later experiments to ensure that data collection methods worked as planned, and to highlight any potential difficulties for full-scale experimentation.

A simple pick and place assembly task using **Lego** bricks was used to replicate small-scale industrial assembly tasks at a low experimental cost to allow for many replications if necessary. The experiment took place in a strictly controlled environment, which allowed closer observation of key variables, but was a less accurate representation of the industrial tasks it was aiming to replicate. Participants were gathered at an innovation event and came from a variety of backgrounds. The basic procedure was as follows:

- Participants were given a brief verbal description of the task and how to use the AR application
- Completion of simple assembly task, following AR assembly instructions on a mobile device provided by the author
- Data analysis using graphical methods (Section 4.5.3) and univariate statistical methods (Section 4.5.2)

As this was a preliminary study, rather than a substantive experiment, no comparisons were made to a control condition because the aim was to identify potential weaknesses in the methods rather than to gather data.

4.4.2 Trials 1-3: User Interaction in AR

Research Objective 2 - To determine the most effective way of presenting AR procedural instructions for a simulated industrial task (Chapter 5 and 6)

To answer Research Objective 2, a series of experiments were devised to compare user performance when following several different types of AR instructions, as well as a comparison against traditional paper-based instructions. These trials expand upon Trial 0, using the same Lego assembly but with a wider variety of conditions (Chapter 6). **User Interaction (UI)** factors such as display mode, device type, and interaction method were varied, to examine their effect on a range of key performance measures, the selection of which is discussed in Chapter 4. This research objective was split into three different studies:

- **Trial 1: Mobile AR** – to investigate how UI factors affect performance when following mobile AR assembly instructions (Section 6.3).
- **Trial 2: Wearable AR** – to investigate how UI factors affect performance when following wearable AR assembly instructions (Section 6.4).
- **Trial 3: Whole Dataset** – the two datasets generated in Trial 1 and Trial 2 were combined to explore differences in UI preferences depending on what kind of device was used to deliver AR instructions (Section 6.5).

A fully factorial design of experiments (Table 4.10) was most appropriate to capture all possible combinations and capture any interaction effects, as well as isolating the effect of each individual factor as recommended by (Santos et al., 2014) in Section 2.6.2.

Table 4.10 - Factors and Levels

Independent Variables (Factors)		0	1	2
A	**Device Type**	Mobile	HMD	
B	**Interaction Method**	Buttons	Voice	Gesture
C	**Display Mode**	CAD Models	Annotations	Videos

To properly assess this complex dataset, multivariate statistical techniques were used as described in Section 4.5. The procedure for these trials was as follows:

- Pre-experiment survey to capture participant demographics and experience level (Appendix D.2)
- Brief verbal description of the tasks, and demonstration of how to use and access the AR instruction app on the device provided
- Completion of two assembly tasks, one using AR instructions on the device provided, and one using paper-based instructions. Quantitative research data was captured during this phase either through the instructional app, or via observations
- Post-experiment survey to capture qualitative research data and freeform task feedback from participants (Appendix D.3).
- Data analysis using graphical methods (Section 4.5.3) and multivariate statistical methods (Section 4.5.1)

4.4.3 Trial 4: Novelty and Learning

Research Objective 3 - To investigate the effect of learning and novelty on performance when following AR instructions (Chapter 7)

Chapter 7 aimed to assess the effect of practice and familiarity on assembly performance when using AR instructions. A series of slightly different tasks of a similar nature and complexity were generated, and users were asked to complete one each day for at least 5 days. Virtual research methods were used to allow the task to be performed in the participants' own homes by posting equipment out to participants. Remote research methods of course come with their own challenges and limitations, which are discussed in Section 4.6.

Participants were gathered through an online sign-up sheet, and consisted largely of postgraduate research students and engineers. In this study, univariate approaches to data analysis (Section 4.5.2) were sufficient because the effect of one factor was assessed against each dependent variable in turn. Aside from the virtual nature of this study, the procedure was broadly similar to Trials 1-3:

- Online sign-up sheet / pre-experiment questionnaire to capture participant demographics and experience level, as well as necessary information to deliver experimental kits (Appendix E.1)
- Brief description of task and information on how to use and access the AR application delivered via email (Appendix E.2)
- Completion of a short assembly task, following AR instructions on a mobile device, once a day for at least 5 days
- Data analysis using graphical and univariate statistical methods (Section 4.5.2 - 4.5.3)

4.4.4 Trial 5 and 6: Engineering Training and Education

Research Objective 4 - To explore novel methods of incorporating MR technologies into engineering training and education (Chapter 8 and 9)

To answer Research Objective 4, two novel ideas for how MR could be incorporated into the world of technical education were explored. Chapter 8 proposes that AR technology has applications in vocational learning. To replicate some of the techniques that might be taught to apprentices in the offshore wind industry, Trial 5 was devised to examine the success of an MR app to guide users through the task of diagnosing faults on a three-phase power supply.

This too was carried out using virtual research methods (Section 4.6), using a sample of volunteers similar in demographics to those in the previous chapter.

The experimental procedure was as follows:

- Online sign-up sheet / pre-experiment questionnaire to capture participant demographics and experience level (Appendix F.1)
- Brief description of task and information on how to use and access the AR application given via email (Appendix F.2)
- Completion of a short simulated diagnostic task, using mobile AR instructions with varying levels of support, depending on users' experience level with 3 phase power
- Post-experiment questionnaire to capture qualitative performance data and freeform feedback from participants (Appendix F.4)
- Data analysis using graphical methods (Section 4.5.3) and univariate statistical methods (Section 4.5.2)

Chapter 9 however focuses on on-the-job training, using AR as a novel way to teach inexperienced users basic Cobot programming skills. This chapter features Trial 6, a case study, so while data was collected on both qualitative and quantitative performance metrics, there was no baseline against which to compare so complex statistical analysis was not possible. Instead, graphical methods are used to examine the data, and comparison of means was used to compare results between participants. Though perhaps this was not as robust as thorough statistical analyses, it was sufficient for a proof of concept to indicate whether future work in this area should be pursued. Unlike the studies presented in Trials 1 - 5, this investigation took place on site at Booth Welsh, an engineering services company, and participants were gathered through sampling employees at Booth Welsh. This lends an added element of realism to the study, which may have been lacking in more controlled lab-based studies earlier in the thesis. The experimental procedure was as follows:

- Pre-experiment questionnaire to capture participant demographics and experience level (Appendix G.4)
- Brief verbal description of task and guidance on how to access and use AR instructions
- Completion of a Cobot training task by following AR guidance on the mobile device provided
- Post-experiment questionnaire to capture qualitative performance data and freeform feedback from participants (Appendix G.4)
- Data analysis using graphical methods (Section 4.5.3) and univariate statistical methods (Section 4.5.2)

4.5 Data Analysis

As noted in the Literature Review (2.7), robust statistical analysis is critical for a productive study. Each study in Chapters 5 - 9 resulted in different datasets, which required different analysis methods, so this section provides only a broad outline of the planned statistical tools.

All data was managed in accordance with the 2018 **GDPR (General Data Protection Regulations)** legislation with the basis for processing data being informed consent. Only adults over the age of 18 were permitted to take part, and a sign-up sheet that included a Participant Information Sheet and Consent Form (Appendix C - Appendix G) was used to ensure only those who consented took part. No sensitive data was collected, and all experimental data were pseudo-anonymised and stored against a unique participant ID so that those taking part could not be identified.

4.5.1 Multivariate Statistics

To achieve Research Objective 2, it was necessary to consider multiple independent variables and their effect on the four different dependent variables discussed in Section 4.2. This makes the data multivariate in nature, and so **Multivariate ANalysis Of VAriance (MANOVA)** was used to compare variance between the groups, to determine if there is more variation between the categories than can be attributed to random variations in the underlying population. A one-way MANOVA allows each independent variable to be analysed separately (Figure 4.1, Hair et al., 1998).

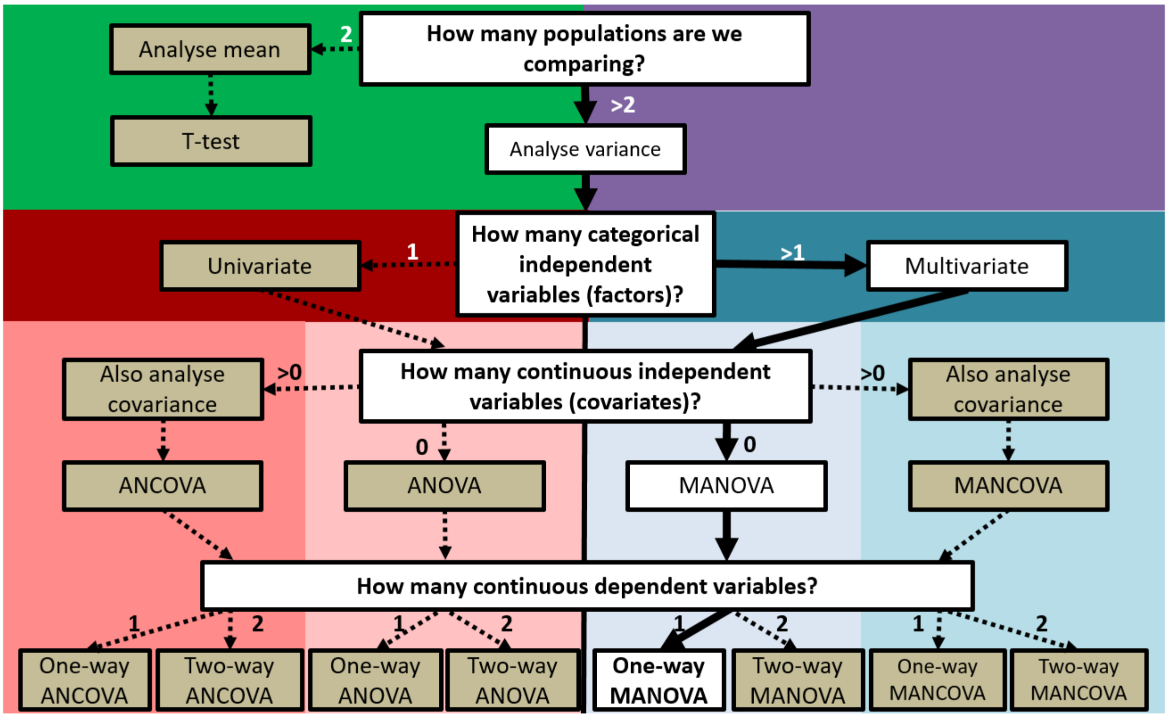


Figure 4.1 - Diagram to show the method of analysis based on data structure

For MANOVA analysis to be valid, the data must meet certain assumptions. These assumptions and the methods of testing for them are outlined in Table 4.11.

Table 4.11 - Assumptions of the MANOVA hypothesis test

Assumption	**Test**	**Required Result**
Continuous Dependent variable	Are ER, TCT, TLX and SUS all continuous?	Y
Independent Categories	Independent factors? 2+ categories?	Y
Independence of Observations	Each participant is a single observation?	Y
No significant outliers	Boxplot and IQR	$\bar{x} \pm 1.5 \times IQR$
Normality	Skewness	Close to 0
	Kurtosis	Close to 3
	Shapiro-Wilks	> 0.05
Homoscedascity	Levene's Test	> 0.05
	Box's M Test	

If all assumptions are met, the MANOVA can be performed, using the function *manova()* from R package Stats (R Core Team: R Foundation for Statistical Computing, 2019). Assumptions 1-3 are due to experimental design, so can be accepted as true for all cases outlined in Chapters 5 and 6.

If the assumption of normality is violated the data may be transformed to attempt to achieve an approximately normal distribution. Otherwise, the **Kruskal-Wallis nonparametric test** may be used as an alternative to MANOVA, which is robust to non-normality (Hair et al., 1998) using the *kruskal.test()* function in the '*stats*' package of R (R Core Team: R Foundation for Statistical Computing, 2019). The Kruskal-Wallis test uses the rank of each value to test for differences between groups, rather than the actual data points, and does not assume the data follow any particular underlying distribution.

If the assumption of homoscedasticity (roughly equal variances between groups) is not met, alternative methods of analysis must also be found, such as **Welch's ANOVA** which is unaffected by unequal variances (Hair et al., 1998).

The results of the MANOVA should indicate whether significant differences exist between experimental groups or treatments, however, it does not indicate where the differences lie or in what direction. For this, post-hoc testing will be required. Post-hoc testing refers to statistical analyses carried out after hypothesis testing has detected a significant result. They can determine where differences occur in more detail.

Tukey's Honestly Significant Difference (HSD) test was used to make multiple comparisons between a set of results to determine precisely where significant differences in performance exist between the levels of each variable (Colman, 2015). This was computed using the *TukeyHSD()* function in the '*stats'* package of R (R Core Team: R Foundation for Statistical

Computing, 2019), which uses not just the mean but also considers the variance of each group to make pairwise comparisons to determine where significant differences exist in the results.

In the case that a Kruskal-Wallis test is carried out instead of a MANOVA, Dunn's test can be used to make pairwise comparisons to identify which groups are different (Hair et al., 1998). Moreover, if Welch's ANOVA is used, the Games-Howell post-hoc test may be used (Hair et al., 1998).

4.5.2 Univariate Statistics

For Research Objectives 3 and 4, the data are much simpler, and only one independent variable was manipulated at a time, so it is permissible to examine the effect on each dependent variable independently using **t-tests** – this is explained in Figure 4.1 on 87.

T-tests are a type of inferential statistics used to compare means of two groups, used in hypothesis testing to judge whether a particular condition in an experiment has an effect on the population (Elliott, 2007). As a parametric test, the data must meet some assumptions in order to be valid:

1. *The data are independent*
2. *The data are approximately normally distributed*
3. *The data has homogeneity of variance (similar amounts of variance)*

If the data meets all these assumptions, then the test is deemed to be valid and analysis can continue as planned. The test compares variation within groups to variation between groups. If variation between groups is shown to be larger than that within groups (typically at a 95% confidence level), then it can be accepted that the experimental condition has had an effect on the population.

4.5.3 Graphical Methods

As well as statistical analysis, results were plotted at each stage of the analysis to allow visual inspection of the general shape and spread of data points. The main types of chart used were:

- ***Box and Whisker plots*** - *which show at a glance the median and interquartile range of the data*
- ***Violin plots*** - *which serve a similar purpose to boxplots but also show density of data to give a more detailed picture of the distribution of data*
- ***Histograms*** – *which show frequency density of data by grouping continuous data into bins*
- ***Q-Q (quantile-quantile) plots*** – *a method to compare the actual distribution of data to a theoretical distribution, in this case the normal distribution*
- ***Time series plots*** – *line graphs demonstrating the cumulative time taken for each step of the task*

4.6 Virtual Research Methods

In addition to investigating the most effective method of conveying AR content, it was also important to examine the effects of learning and technological novelty on user performance and acceptance. Therefore, another set of experiments was designed to examine how performance metrics changed as users gained more practice and experience at using AR technologies. These results are presented in Chapter 7. However, in March 2020, the UK entered a period of national lockdown due to the serious health risks posed by the SARS-CoV-2 virus, known as COVID-19. All on-site work considered non-essential (including research not related to healthcare) being strictly prohibited as the majority of the UK was asked to work from home.

This had significant impacts on the planned progress of the PhD project, as in-person experiments involving human beings were prohibited for several months, and considerable restrictions on interaction with other people remained in place until the summer of 2021. With no clear end date to these restrictions, significant adaptations were made to the original research plan to allow studies to be carried out in a virtual manner. Instead of participants coming on site to carry out an assembly task using equipment provided, the experiments were redesigned to be suitable for remote deployment so that users could carry out the tasks on their own devices in their own homes. This meant simplifying the study task to use a reduced amount of equipment, so that a kit of Lego and printed layout sheets could be sent out to users in the post (shown in Figure 4.2, pg. 92).

Figure 4.2 – Example of experimental kits posted to participants

The app itself was updated accordingly to reflect the new simplified task too. One major challenge was that participants and the author were no longer co-located, and so explanation of the task and any support needed now had to take place via email. Troubleshooting was particularly challenging as it was very difficult to tell if problems were due to a design flaw in the app, an issue in the user's environment (such as shadows or occlusion of markers), or even user error. Because of this, several participants dropped out of the study without completing the task and the reasons cannot be identified with certainty.

Another downside to this virtual approach to experimentation was data collection. In the research design described in Chapter 3, and indeed the experiments presented in Chapters 5 and 6, the error rate was measured mostly through observation. Although the app collected data on button presses (as described in Section 5.2.1.3), this only captured errors where the user referred back to on screen instructions to correct them. In-person observations then verified and supplemented the data to include self-corrected errors (without referring to previous instructions) or uncorrected errors. Without the co-presence of the author and participants, this was impossible, and so only that first category of error could be considered. This is a recognised problem in remote virtual research (Ratcliffe et al., 2021); however, it remained the best option to enable safe continuation of research during the height of the COVID-19 pandemic.

Adaptations to the research protocol was not the only impact of the pandemic on this research. COVID-19 poses numerous challenges to the offshore wind and maintenance industries themselves. Thousands of hours of vocational training have been lost, deepening an already severe skills gap in the industry. To mitigate against a further erosion of vocational engineering and manufacturing skills in the UK, new technological solutions are required to enhance and enable practical and work-based learning with minimal human contact. With this in mind, Chapter 8 investigates AR technologies as a supplement for in-person vocational training, when access to on site facilities may be limited. This too was carried out using remote research methods.

4.7 Summary

In this section, key decisions were made regarding the general methods used to investigate the research objectives from Section 2.8.

Section 4.2 outlines the general process behind the experimental details in Chapters 5 - 9. Three independent variables (device type, display mode, and interaction method) were selected alongside four dependent variables (task time, accuracy, cognitive effort, and system usability) to judge the success of various app designs based on common values in the literature as well as the needs of industry. This was done to ensure that the research aligned with both industrial practises as well as standard measures in academia. Another strength is that these variables cover both objective performance (task time and error rate) and subjective measures (cognitive effort and usability), which are both important factors in the success of new technology adoption.

In Section 4.3, a meta-analysis of AR experiments using Task Time as a key factor found a minimum sample size of 24 participants for fully factorial experiments.

While Section 4.4 outlines an overview of each planned study, Section 4.5 goes on to outline the various multivariate, univariate and graphical methods used to analyse the generated data and look for statistically significant relationships between factors.

Section 4.6 discusses some of the necessary changes made to the experimental methods to accommodate restrictions during the COVID-19 pandemic.

However, there are still some limitations to the methods outlined here. Firstly, as the instructions were hosted online, there is a risk of user performance being influenced by quality of internet connection, rather than their actual ability to complete the task. Another main disadvantage is that participants were gathered through a convenience sample at the University, meaning they were largely degree educated male engineers – this is not necessarily representative of the target user (i.e. wind turbine technicians) and certainly is not an accurate reflection of the demographics present in the general public. Therefore, caution should be applied when extrapolating the results of these studies to the general population. To address these concerns, the next chapter (Chapter 5) discusses a pilot study to identify opportunities for improvement.

Experimental design is not discussed in detail at this stage as it was varied depending on the specific goals of the individual study. Instead, these can be found in the respective methods sections of Chapters 5 - 9.

5 Preliminary Study

5.1 Introduction

Before embarking on the experimentation phase of research, a small-scale study, referred to as Trial 0, was used to develop and test the methods described in Chapter 4. In addition, this chapter shows the development of a flexible AR application to deliver assembly instructions, thereby addressing Research Objective 1 - To develop a flexible cross platform AR research tool which can operate using a variety of user interaction modes. This application forms the basis for all experiments in Chapters 6 - 9, though some minor improvements to the research protocol were noted. Therefore, Trial 0 was also an opportunity to ensure that the application was fit for purpose before embarking on more substantive experiments detailed in later chapters.

Based on these early results, there were small changes to the experiments described in Chapters 6 - 9 and these are described in the methods sections of those respective chapters. Initial results from Trial 0 illustrated potential shortcomings in the experimental method and explain why the final methodology was chosen.

5.2 Methods

This preliminary study was performed in person at an internal event at the premises of the industrial partner Booth Welsh. Thirteen people took part. Although Booth Welsh is an engineering services company, participants came from across all business functions.

The study used a simplified version of the assembly tasks used in Chapters 6 and 7 for portability and convenience. Due to time constraints, the participants completed only one assembly, using AR instructions (CAD display mode, button interaction), and the pre- and post-experiment questionnaires from Chapter 3.3.1 were not implemented. Brief verbal instructions on how to use the app were given beforehand, and assistance was given when requested.

5.2.1 AR App Design

This section describes the design of a flexible web app to deliver AR instruction guidance whilst easily being able to change various UI factors and collect research data to help measure the variables discussed in Section 4.2. A baseline app is described, covering basic functionality to deliver AR instructions for a short assembly task, thus meeting Research Objective 1. The app was then adapted in later trials, to meet different objectives. These adjustments are described in the Methods section of each chapter (Sections 6.2, 7.2, 8.2, and 9.3 respectively).

After reviewing the options for app development in Section 2.3.4 of the literature review, a web app approach has the potential to fulfil all the basic requirements of the proposed app, as well as offering key benefits such as web deployment, cross-device functionality and IoT integration. The use of web technologies allowed a hardware agnostic approach, which was beneficial during the experimentation stage of this research, making it relatively quick and easy to deploy very similar apps on different device types to compare performance. The downsides of being reliant on a data connection could be overcome in full-scale implementation by keeping rendered objects simple and mainly using cloud services for storage, not computation. Therefore, web technologies were adopted for AR app development, allowing Research Objective 1 (development of a cross-platform research app) to be met. Sections 5.2.1.2 and 5.2.1.3 explain the functionality of the app and description of how data was collected to aid the research process.

5.2.1.1 Software and Development Languages

The NodeJS (OpenJS Foundation) runtime environment was used to act as a web server, with JavaScript as its scripting language. NodeJS is generally considered faster than alternatives such as PHP/Apache, due to its lightweight function and asynchronous processing which makes it an excellent choice for applications, such as this one, where real-time data is desirable (Chaniotis et al., 2015). It also simplified the development process, as the front-end of the application was also written using JavaScript. NodeJS can be hosted on a local machine, in this case a Raspberry Pi (Raspberry Pi Foundation), but for future scalability, 24/7 access and to ensure a fixed IP address, cloud services such as Azure (Microsoft, 2021) would be recommended for full-scale deployment.

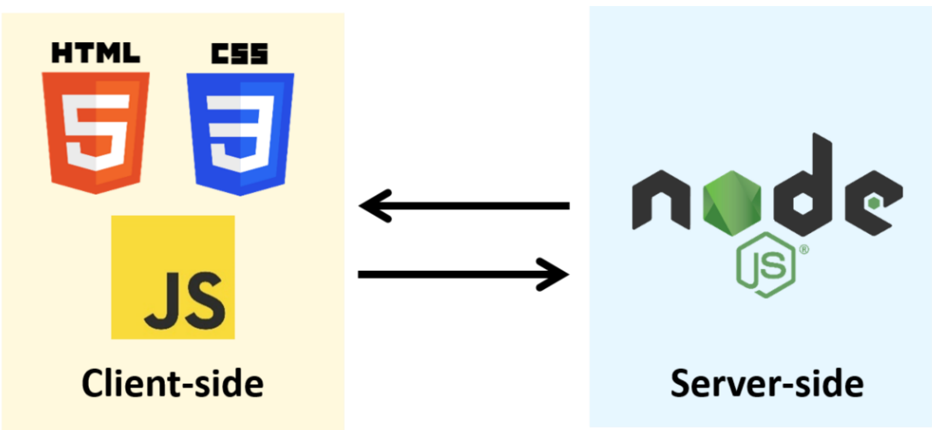


Figure 5.1 – AR application web technologies

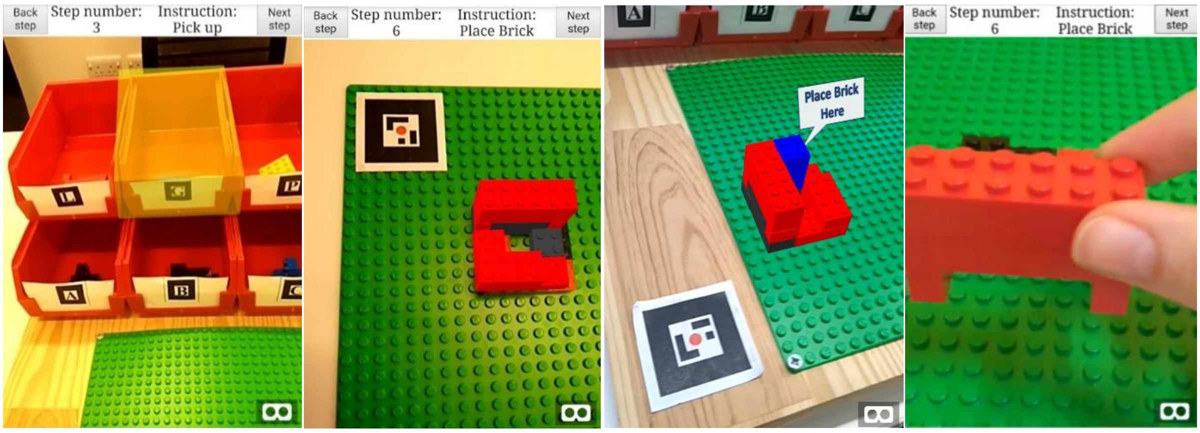
Much of the app used the A-Frame framework (A-Frame), which is built on top of the Three.js **Application Programming Interface (API)** to display 3D graphics over the web (Cabello, 2010). Both A-Frame and Three.js are designed to work with the WebXR specification for AR and VR content on the web, making the app compatible with the majority of most modern web browsers (World Wide Web Consortium (W3C), 2020). **HyperText Mark-up Language (HTML)** provided the structure of the webpage, while **Cascading Style Sheets (CSS)** defined the style and design of the content.

5.2.1.2 Functionality

To meet Research Objective 2 (exploring how presentation of AR content affects performance in assembly tasks), the app was developed to guide users through a sample task, described in Section 5.2.2. Thanks to the use of web-apps, changes could be made to a variety of UI factors without affecting the overall look and feel of the app, thereby avoiding introducing any extraneous variables into later experiments. The three factors considered were display mode, interaction method, and device type.

Firstly, display mode – how the instructions are conveyed visually to the user. The AR instructions highlighted the location of the target object (in the case demonstrated here, a Lego brick) by overlaying a coloured cuboid onto the user's view (Figure 5.2 *(a)*). Then, one of the methods below indicated to the user where to place the target object within the working area:

- ***CAD (Computer Aided Design) Models*** *– a 3D representation of the parts at the location and orientation of the intended placement (*Figure 5.2 *(b)).*
- ***Annotations*** *– written instructions in the 3D environment describing the action required whilst indicating the location (*Figure 5.2 *(c)).*
- ***Video*** *– a pre-recorded video to show the user where to place the parts (*Figure 5.2 *(d)).*



(a) (b) (c) (d)

Figure 5.2 – AR guidance (a) highlighting the target object, and the target location using (b) 3D models, (c) virtual annotation, and (d) in-situ video

The app had two options for how users could control and interact with AR content, i.e., the interaction method:

- ***Native Interaction*** *– the built-in mode of content control in the chosen device. For the HMD, this was using the pinch gesture and cursor to select and interact with objects. For the mobile device, this was the familiar touchscreen interface*
- ***Voice Control*** *– voice commands, interpreted using the annyang.js JavaScript library (Ater, 2016), used to control content. Commands included "Next" or "Okay" to progress forward through instructions, and "Back" or "Previous" to revisit a previous instruction.*

Finally, the application was designed to be compatible across platforms so that the effect of device type on user performance could be explored. The two devices considered were:

- ***Mobile phone*** *– Android phone with chrome-based browser*
- ***Head Mounted Display*** *– Microsoft HoloLens 1st Generation*

5.2.1.3 Research Tools

In addition to the basic function of the app (i.e., guiding users through a set of instructions), some features were included to collect research data. For example, when using the app, timestamps were recorded every time the 'next' or 'previous' buttons were used. This provided a time taken for each step, as well as an overall task time. Further, this data was also used to infer information about the number of errors made by users – for example, if the user pressed the previous button to go back from step 5 to step 4, then carried on forwards, one might infer that this indicated an error made at step 4 that was realised at step 5 and corrected. Of course, this is only a proxy for error rate and not a perfect measure as users may have made errors that remained uncorrected, or may correct errors without going back in the instructions. Therefore, wherever possible this was supplemented by experimental observation.

A 'helper' web page (Figure 5.3) was also developed for recording experiments carried out using paper instructions.

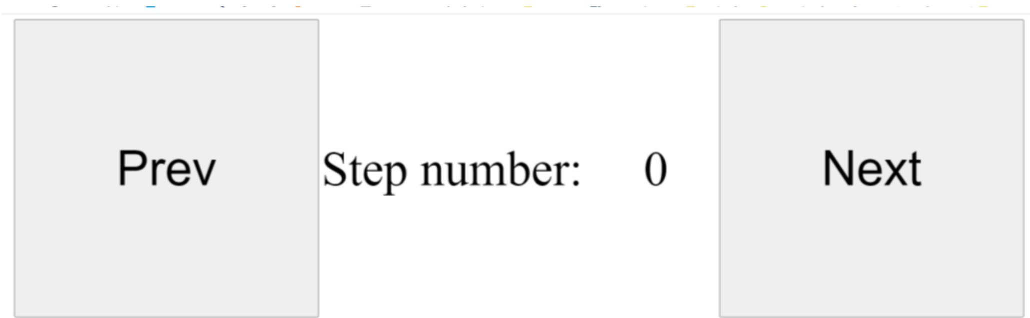


Figure 5.3 – 'Helper' web page for recording task time when using paper instructions

The author had access to this web page and used 'previous' and 'next', to record timings as the participant moved forwards and backwards through each step of the instructions.

5.2.2 Study Task

While later studies in Chapter 6 - 9 all used different tasks, the initial task chosen for use in experiments was the assembly of a Lego puzzle cube to simulate industrial assembly tasks. It was based loosely on Funk et al.'s standard **Duplo** activity, which involves stacking Duplo bricks to form a wall (Funk et al., 2015b). One of the strengths of AR has over traditional paper instruction formats is the ability to move around and view assemblies from different angles. Therefore, rather than placing single bricks in a line like in Funk et al.'s wall task, this study used a puzzle cube where subassemblies of bricks in a variety of symmetrical and asymmetrical shapes needed to be placed in the correct position and orientation. This takes better advantage of the visualisation capability possible with AR by adding rotational complexity to the assembly.

Participants were presented with the Lego puzzle cube instructional app, which guided users to select one subassembly at a time from trays, and then assemble them in a specific location. Participants were pseudo-anonymised using a 3-digit number, starting with a 0 to denote that they were a part of Trial 0. (e.g., 0XX).

In the paper condition, users can see all instructions at once and are directed to look for the corresponding letter on the instruction and to match the construction shown in the photo (Figure 5.4, pg. 104).

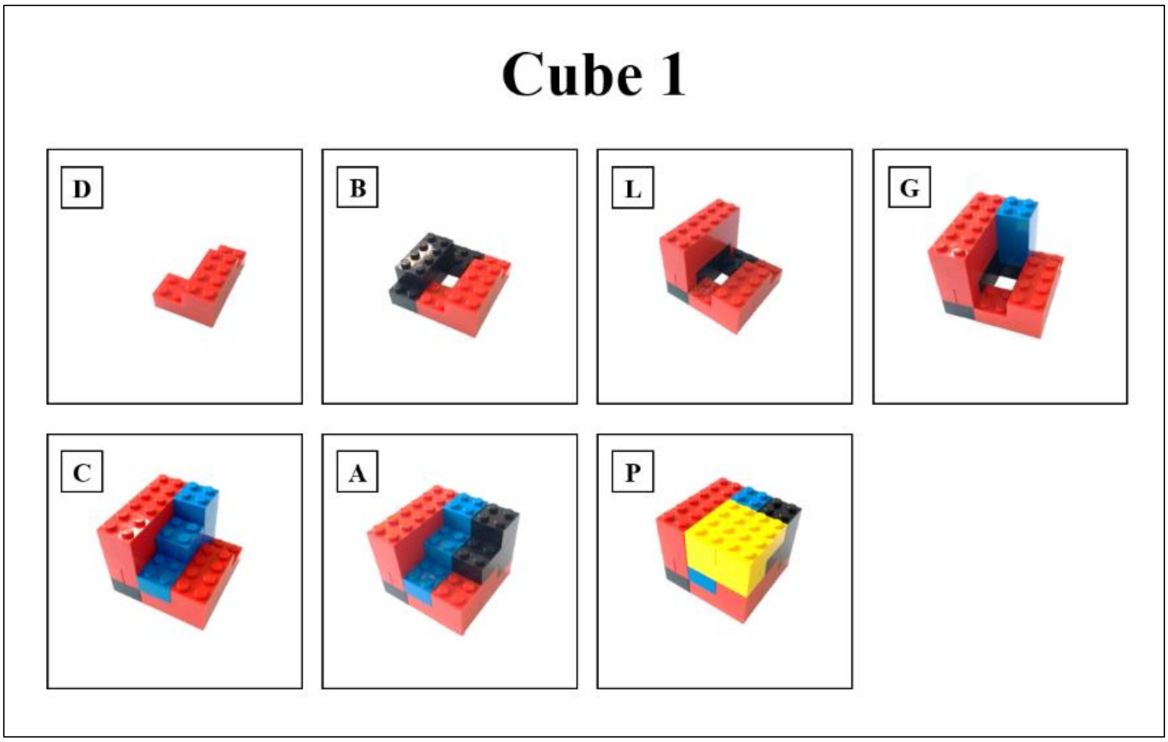


Figure 5.4 - Example of paper assembly instructions used in task

In the AR condition, the location of the brick to be picked is highlighted by a coloured block overlaid onto the users' view (Figure 5.5 (a) 'pick' instructions).

In later experiments (Chapter 6), the user is guided to place the brick in a location variously by a CAD model superimposed onto their vision, floating text boxes and videos of the assembly.

However, in this preliminary study, only the version of the app using CAD models was used (Figure 5.5 (b) 'place' instructions, pg. 105).

(a) (b)

Figure 5.5 - Example of screenshots from mobile AR instructions for the tasks (a) 'pick' instruction, and (b) 'place' instruction

Due to time constraints, pre- and post-experimental surveys were not implemented during Trial 0, and therefore the dependent variables for this study were Task Completion Time and Error Rate as shown in Table 5.1:

Table 5.1 – Description and shorthand for dependent variables in this chapter

Task Completion Time	Time in seconds from start of task to completion	**TCT**
Error Rate	Number of errors (whether corrected or uncorrected) made during the task	**ER**

5.3 Results of Trial 0

Table 5.2 shows the average time to complete the task, which was a little under 3 minutes, with a standard deviation of around 1 minute, suggesting a lot of individual variation between participants.

Table 5.2 - Mean and Standard Deviation of total task time during Trial 0

	Total Task Time (s)	Average time per step (s)	Average time per pick step (s)	Average time per place step (s)
Mean	158	12.2	2.33	8.83
Standard Deviation	60.6	4.66	1.45	7.74

Due to this large variation in individual results, it was decided that future studies should use a baseline result to help control for individual differences. All participants were to complete the task once using AR instructions and once with paper instructions.

The scores for each dependent variable in the AR condition were then subtracted from the baseline performance using paper. An example is provided for clarity (Table 5.3, Equation 2).

Table 5.3 - Definition of experimental KPIs

Symbol	**Definition**
ER_p	Error Rate (#) using paper instructions
ER_{ar}	Error Rate (#) using AR instructions
ΔER	The difference in performance between two conditions

Equation 2 – Example to demonstrate how variables are calculated:

$$ER_{ar} - ER_p = \Delta ER$$

The rest of the dependent variables can be calculated and interpreted as shown in Table 5.4.

Table 5.4 - Dependent variables (factors), calculation and meaning of possible values

Dependent Variables	Calculation	Positive value	Negative value
Error Rate (ΔER)	$ER_{ar} - ER_{p}$	AR leads to more errors	AR leads to fewer errors
Task Completion Time (ΔTCT)	$TCT_{ar} - TCT_{p}$	AR leads to slower task completion	AR leads to faster task completion
NASA-TLX Score (ΔTLX)	$TLX_{ar} - TLX_{p}$	AR increases the cognitive effort	AR decreases the cognitive effort
System Usability (ΔSUS)	$SUS_{ar} - SUS_{p}$	AR improves usability	AR decreases usability

The order participants perform the tests in (i.e., paper followed by AR, or AR followed by paper) was alternated and used as a blocking factor, so at least two runs of each treatment are needed to balance out order effects. The work was broken down into several studies, to make it more manageable. Data collection, however, was standardised so that data can be analysed both within each study and across studies. Although four people made at least one error (average values shown in Table 5.5), all were corrected at some stage during the assembly, so the final product was completed correctly.

Table 5.5 – Mean and Standard Deviation of error count during Trial 0

	Total Error Count (#)
Mean	0.538
Standard Deviation	0.929

Chart 5.1 (pg. 108) shows that Step 1 (locating and selecting the first brick of the assembly) was much longer than any of the other assembly steps. This was due to Step 1 incorporating the time taken for the page to load. This is considered an extraneous factor, as it is more dependent on internet connection than user performance, so Step 1 is discarded from analysis going forwards.

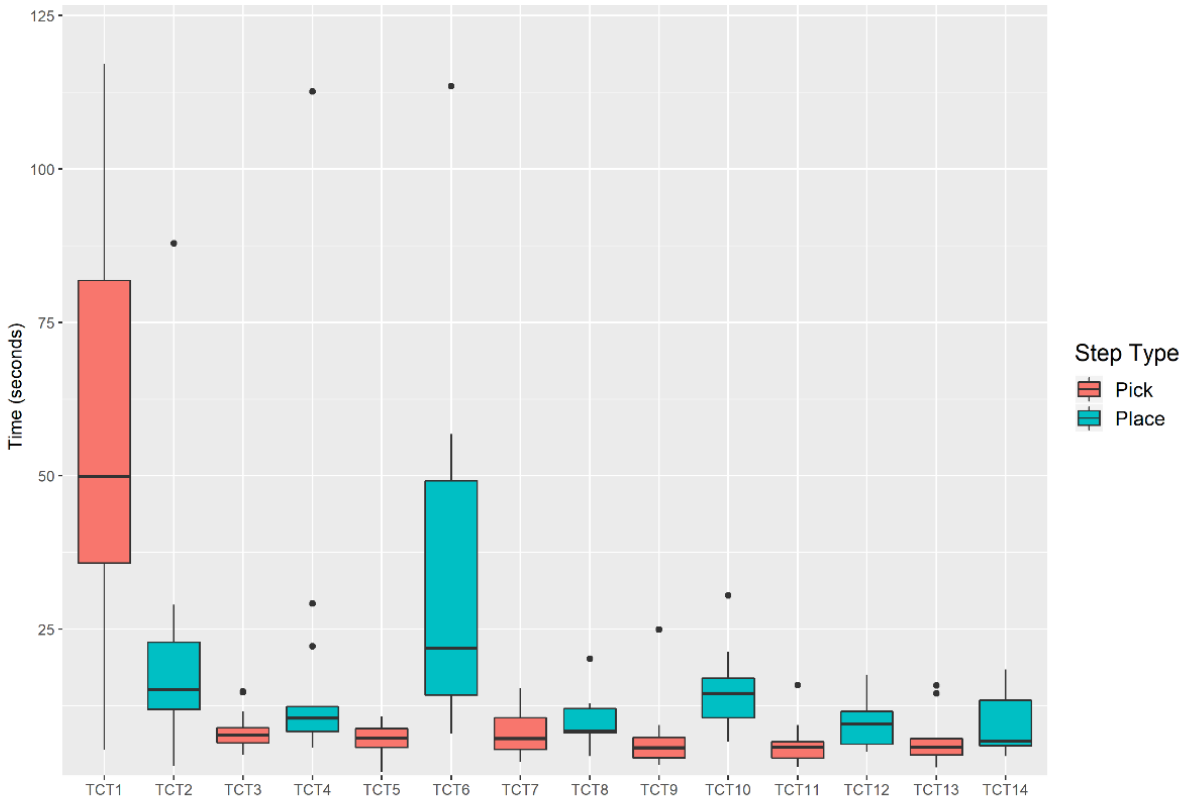
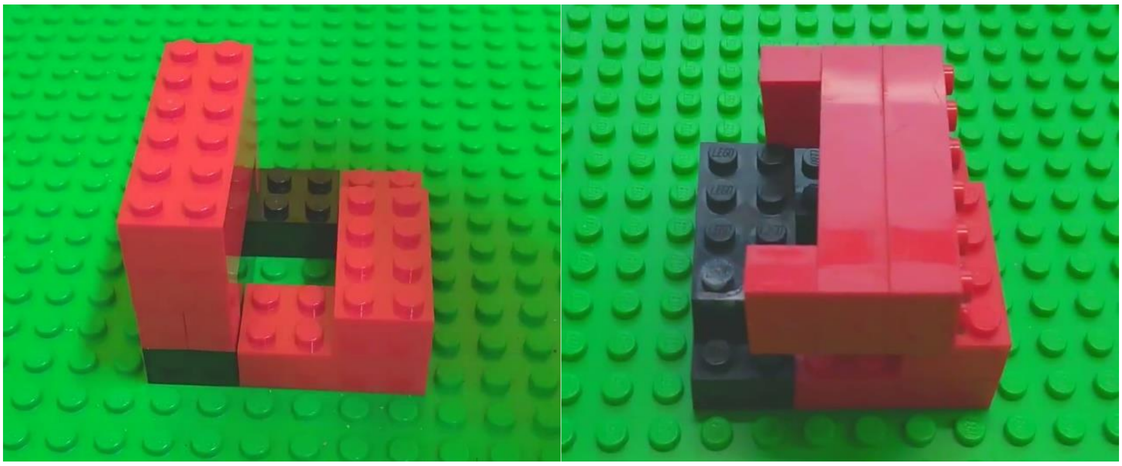


Chart 5.1 – Boxplot showing times taken for participants to complete each step in Trial 0

From Chart 5.1, the 'place' steps, in which users had to locate the correct position to assemble a new part in, generally took longer than the 'pick' phase, selecting the relevant part from the grid). In general, there is a trend of times reducing for each type of step as the task goes on, suggesting there is some level of adjustment and learning how to use this new technology.

The exception to this is Step 6: five users made the same mistake (three self-corrected before moving onto the next step, hence do not show up in the figures in Table 5.5). Specifically, they attempted to place the Lego block sideways (Figure 5.6 (b)).



(a) (b)

Figure 5.6 – Step 6 from Lego puzzle cube assembly number 1 (a) performed correctly, and (b) with the incorrect orientation

This phenomenon is observed in Chart 5.2 and Chart 5.3 (pg. 110), where Step 6 is noticeably longer than the other steps in the assembly. This raises some concern that when using this new technology, participants may be overly trusting or reliant on the AR, and forget learned behaviours such as standard Lego assembly techniques.

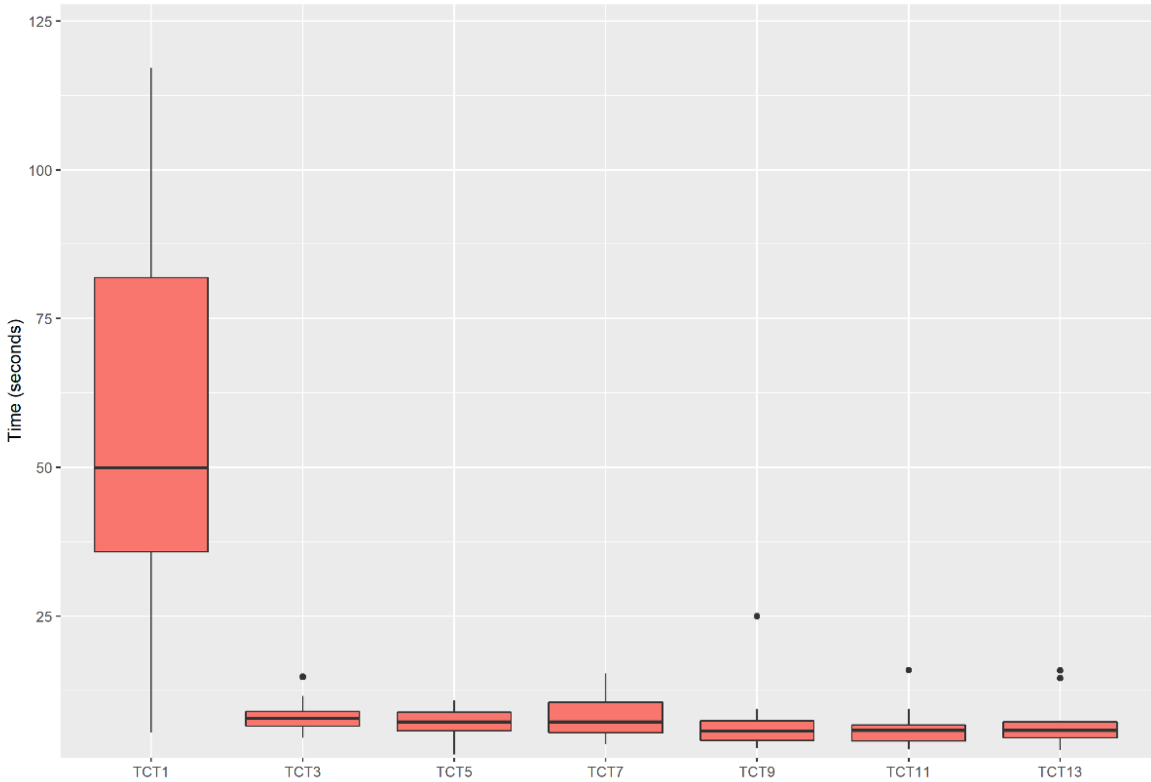


Chart 5.2 - Boxplot showing times taken for participants to complete 'pick' steps in Trial 0

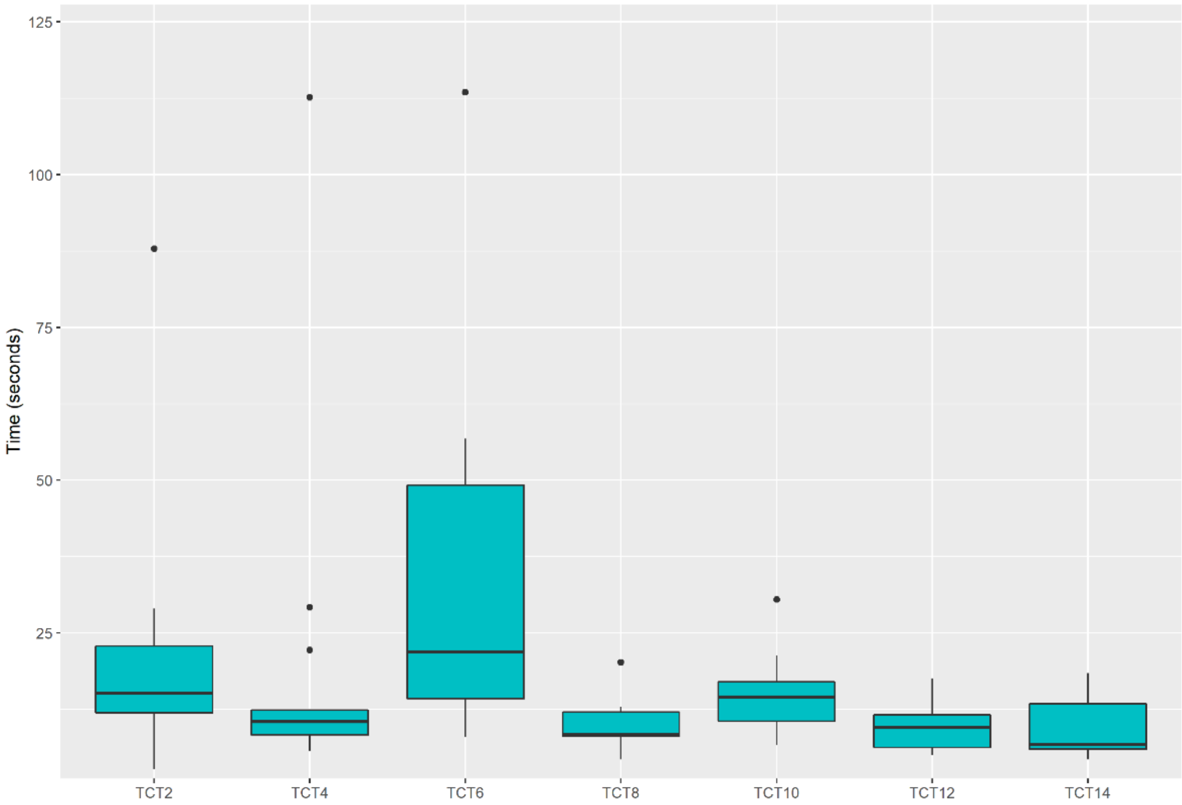


Chart 5.3 - Boxplot showing times taken for participants to complete 'place' steps in Trial 0

Chart 5.4 (pg. 111) shows how each participant progressed through the steps of the assembly task. It suggests an acceleration as participants move through the various stages of the assembly. It also makes clear the persistent error on Step 6. Moreover, errors were often corrected without the need to go back and re-inspect any previous instructions.

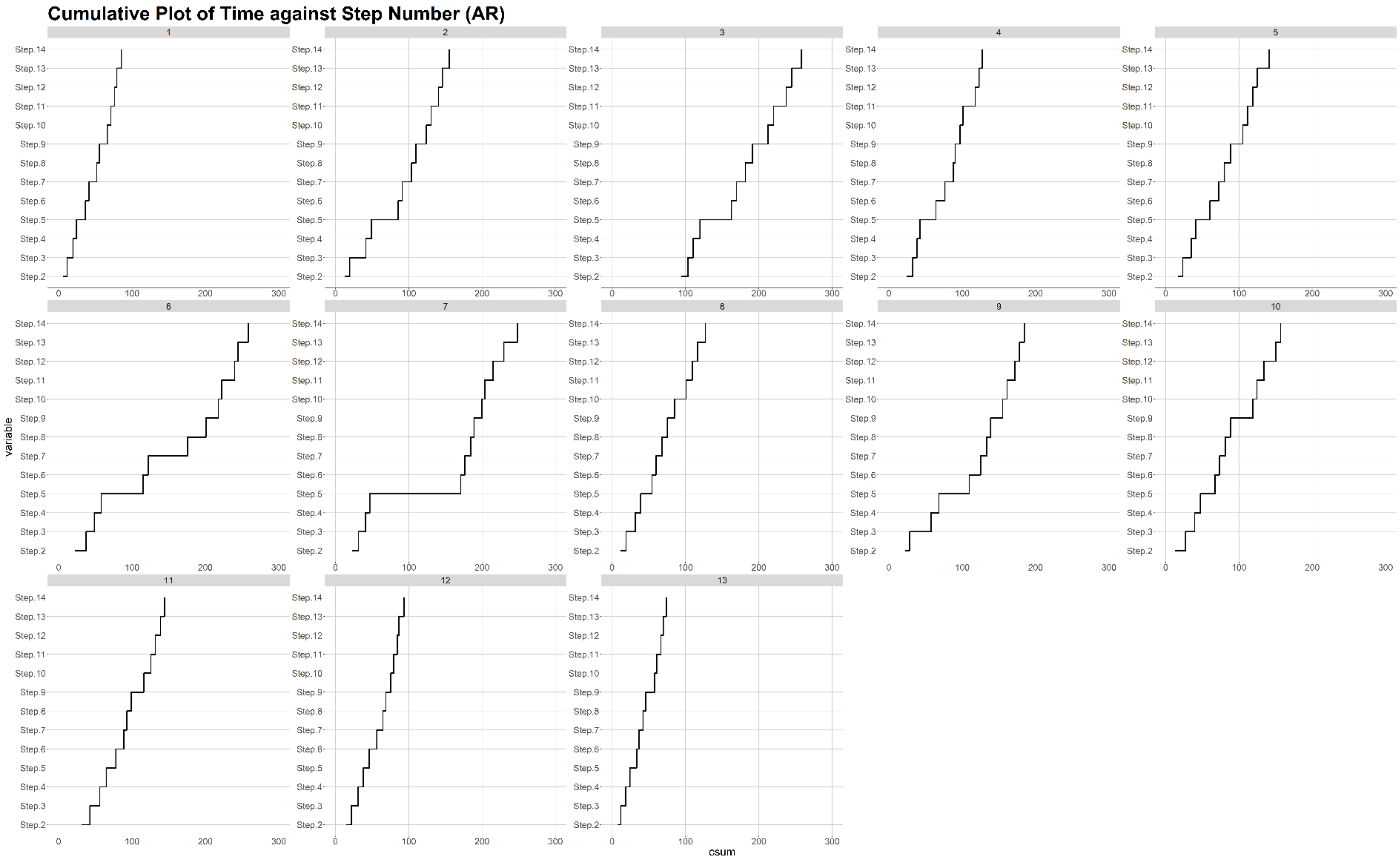


Chart 5.4 - Time series of step number against cumulative time taken to complete the task (seconds)

5.4 Summary

This chapter served to address **Research Objective 1** by describing the functionality and design of the AR application developed to deliver instructions and collect research data. Trial 0 was devised to verify that the AR application, as well as the research protocol outlined in Section 4.4, was appropriate for use in later experiments. Following Trial 0, some minor changes to research methods were made in response.

As noted in 5.3 when discussing the spread of task times, there is a lot of individual variation in task performance. The results of Trial 0 indicated that in future experiments, a test value that uses the user's performance with paper instructions as a baseline against which performance is compared, would be preferable to using raw results. This idea was explored in 5.3 and all experiments in Chapters 6 - 9 used this 'delta' value as a metric unless specified otherwise.

Future analyses did not consider Step 1, due to page loading time overwhelming the time taken to perform the assembly step. Despite excluding Step 1 from the analysis, the time taken for Steps 2 onwards still seemed generally to accelerate, even though complexity of the step should be very similar. This suggested the presence of a learning effect as users adjust to the unfamiliar technology – Chapter 7 explores this further.

The large task time and repeated errors made on Step 6 also remain an obstacle; however, there is no clear explanation for this behaviour at this stage. It is possible that the new digital technology takes a lot of cognitive effort, and this is impairing users from accessing their usual spatial reasoning ability. An alternative explanation is that users are so trusting of the new digital technology that they are not questioning their interpretation of the visual information, even when it appears to be impossible to perform the action in that way. Further experiments were observed closely to look for other examples of this phenomenon and attempt to gather more data to determine an explanation.

In this study, all participants carried out the same assembly task. For full-scale experiments, two similar puzzle cubes were designed so that users could complete one with paper instructions and one with AR. Both puzzle cube assemblies were of similar complexity, however one had more steps than the other does, so data gathered about the final two steps on Cube 2 was discarded.

6 An Evaluation of User Interaction Factors in AR Assembly Instructions

6.1 Introduction

This chapter investigates **Research Objective 2: To determine the most effective way of presenting AR procedural instructions for a simulated industrial task**. This falls into three main questions:

1. *Are AR or paper-based instructions a more effective guidance system for participants performing a simple assembly task?*
2. *Is voice control or gesture control a more effective mode of interaction with AR guidance systems when performing a simple assembly task?*
3. *Are AR instructions easier to understand when presented as text, 3D models, or animations when performing a simple assembly task?*

Using the study design from Section 4.4 and a modified procedure following the results of Trial 0 (Chapter 5), the general methods employed to answer these questions are outlined in Chapter 5, while results are split into three sections:

- **Trial 1: Mobile AR** - a series of experiments to compare different User Interaction factors that may affect performance using mobile devices to convey AR content to the user, as well as a more general comparison to traditional paper instructions (Section 6.3).
- **Trial 2: Wearable AR -** this study mirrored that in Trial 1, but this time using a wearable AR device to carry the instructions (Section 6.4).
- **Trial 3: Whole Dataset** – this section combines the datasets from both previous trials to allow a comparison of the two device types (Section 6.5).

6.2 Methods

The studies laid out in Sections 6.3 and 6.4 were carried out under relatively controlled conditions on the main campus at **Strathclyde University (UoS)**. Forty-eight participants were gathered from colleagues at the university, and volunteers responding to posters on campus advertising the call for participants. This exceeds the minimum of 24 specified in Section 4.3, so results can be accepted with reasonable confidence that differences in the data will indeed be detected if they truly exist. There were no strict criteria for who could or could not take part, though participants were asked to report if they had any vision or mobility issues that might affect their ability to complete the task. Table 6.1 provides a general summary of participant demographics, and Appendix D.2 contains full results of the pre-experiment survey used to identify participant backgrounds.

Table 6.1 – Summary of participant demographics showing how many participants fell into each category

Age	**18-25**	**26-40**	**41-65**		
	23	23	2		
Gender	**Male**	**Female**	**Other**		
	39	9	0		
Role	**Researcher**	**Undergrad**	**Other**		
	35	11	2		
AR Experience (1-5)	**1**	**2**	**3**	**4**	**5**
	23	15	8	1	1
Technical Skills (1-5)	**1**	**2**	**3**	**4**	**5**
	0	2	9	26	11
IT Skills (1-5)	**1**	**2**	**3**	**4**	**5**
	0	0	10	26	12

As specified in Section 4.2, the factors investigated were Device Type, Interaction Method and Display Mode, each of which contained up to three levels. A fully factorial design of experiments allowed identification of any interaction between these factors (Table 6.2).

Table 6.2 – Levels and factors investigated

Factors	**Levels**	**# participants per level**
Device Type	Wearable (HoloLens)	24
	Mobile (Android)	
Interaction Method	Native Interaction	24
	Voice Commands	
Display Mode	3D Models	16
	Text Annotations	
	In-Situ Videos	

The AR app used is the same as the one described in Trial 0 in Chapter 5. However, for this study it was adapted to enable all variants of the User Interface (UI) as listed in Section 4.2.3. The methodology from Section 4.4.2 was broadly followed, with two concessions made from the findings of Chapter 5. Firstly, to exclude the first step of the assembly from data analysis, and secondly to include a short practice task before the main assembly. Participants were invited to complete the tasks in their own time, using both written instructions on paper, and AR instructions that were accessed using either an Android mobile phone (Section 6.3) or Microsoft HoloLens (Section 6.4) provided to them, with the application pre-loaded. After a brief introduction to the aim of the study, participants filled out a pre-experiment questionnaire to gather data on their background (Appendix D.4).

After this, the following two items happened – the order of which alternated between users to counterbalance order effects:

- Participants were asked to complete a short Lego assembly using paper instructions with materials provided
- Participants were introduced to the device and allowed a short practice task (stacking 3 bricks atop one another) before asking them to complete a short Lego assembly using the AR instructions and materials provided

Finally, participants filled out a post-experiment survey (D.3) to capture their experience and any feedback on the process.

The four factors investigated in this chapter are summarised in Table 6.3, along with their abbreviated names:

Table 6.3 – Description and shorthand for dependent variables in Trials 1-3

Task Completion Time	Time in seconds from start of task to completion	**TCT**
Error Rate	Number of errors (whether corrected or uncorrected) made during the task	**ER**
Cognitive Load	Mental effort required to complete the task, measured using the **NASA-TLX** scale (Hart and Staveland, 1988)	**TLX**
System Usability	Perceived ease of use of the system, measured using the System Usability Scale (Brooke, 1996)	**SUS**

6.3 Trial 1: Mobile AR

Different variations of mobile AR apps were compared, as well as traditional paper instructions. A table of the full raw results is provided in Appendix D.4, while Sections 6.3.2.1 and 6.3.2.2 detail the most important results and their interpretations. Participants are denoted by 3 digits starting with a 1 (i.e. 1XX) to indicate being part of Trial 1.

Please note: *the results and information contained in this section were presented at the International Conference on Human-Computer Interaction, 2020*[3].

6.3.1 Assumptions

Data for this experiment was tested against the criteria from Sections 4.5.1. Task time met requirements for **skewness**, **kurtosis** and normality (Table 6.4).

Table 6.4 – Tests for Normality on each individual performance measure

Variable	Skewness	Kurtosis	Shapiro-Wilks Test
TCT (Task Completion Time)	-0.09745 approx. symmetric	2.54507 mesokurtic	0.907696 approx. normal
ER (Error Rate)	0.573603 moderately skewed	3.538578 leptokurtic	0.018371 significant deviation
TLX (Task Load Index)	0.86603 moderately skewed	4.042611 leptokurtic	0.088335 approx. normal
SUS (System Usability Scale)	-1.78455 highly skewed	8.392143 leptokurtic	0.000914 significant deviation

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[3] *SMITH, E., SEMPLE, G., EVANS, D., MCRAE, K. & BLACKWELL, P. Augmented instructions: analysis of performance and efficiency of assembly tasks. International Conference on Human-Computer Interaction, 2020. Springer, 166-177. Adapted with permission from © Springer Nature Switzerland AG 2020.*

Visual inspection of the histogram (Chart 6.1) confirms that the data appears to be approximately normally distributed.

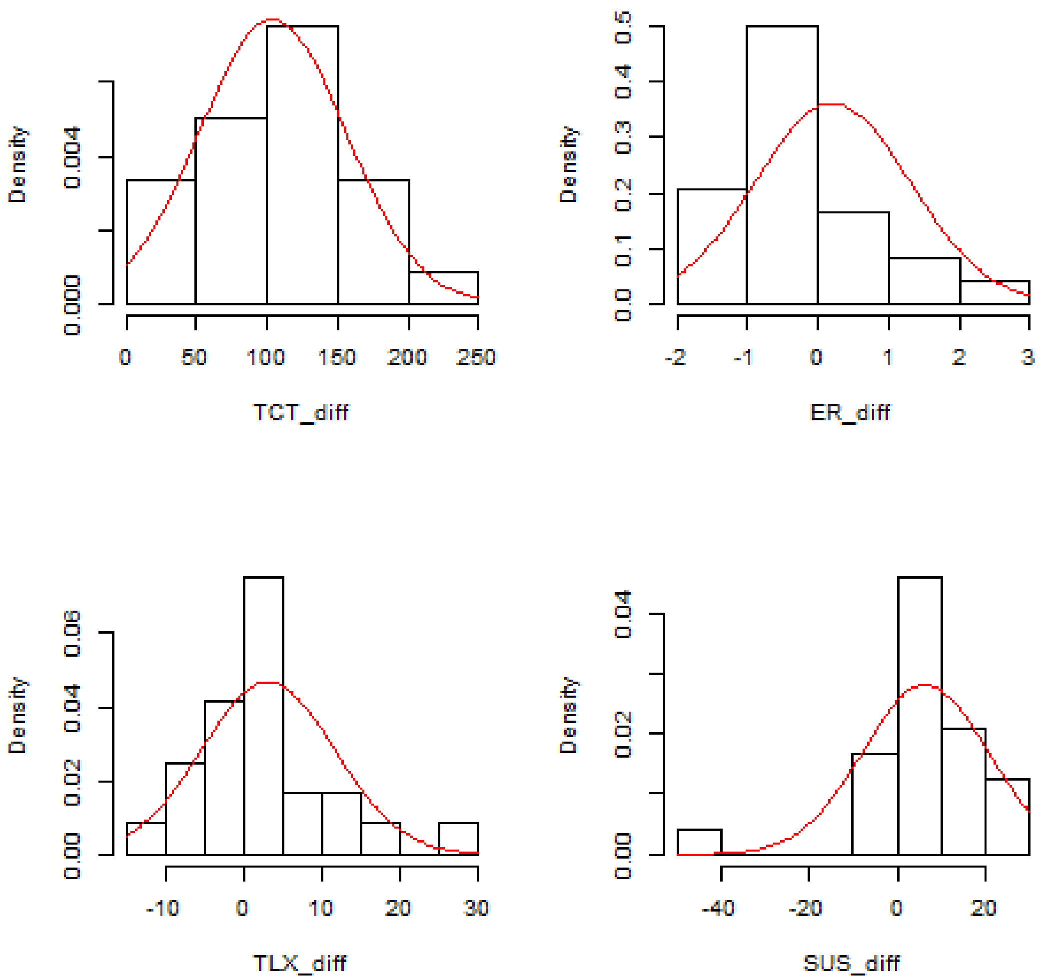


Chart 6.1 – Histograms showing univariate distributions of each dependent variable including line of best fit

Error rate is moderately skewed and leptokurtic (i.e., having wider tails at the extremes of the distribution), however MANOVA analysis is considered robust to these assumptions (Hair et al., 1998) so this is not too great a concern. Failing the **Shapiro-Wilks** test is more significant so some scepticism must be applied to the results of this performance measure. The distribution appears by visual inspection of Chart 6.1 to be close to normal, and Shapiro-Wilks is known to be inaccurate in relatively small sample sizes so while caution should be applied; there should still be value in the result (Hair et al., 1998).

TLX score (cognitive effort) is similarly slightly skewed and leptokurtic but passes the Shapiro-Wilks test and appears approximately normal by visual inspection, so analysis can proceed as planned (Section 4.5.1). The system usability score does not meet any of the univariate assumptions required for MANOVA, so caution was applied when interpreting the results of this performance measure.

Conditions for multivariate normality must also be met, as MANOVA is a test for multivariate data. This can be assessed visually using a **Q-Q plot** of all 4 dependent variables (Chart 6.2, pg. 122) created using the *ggqqplot()* function in R package *ggpubr* (Kassambaara, 2020). There is little deviation from the diagonal lines for any of the measured factors, indicating the dataset can be considered approximately normally distributed. The grey shaded area shows a confidence interval of 95% as per default settings of *ggqqplot()*.

In conclusion, the data for this study satisfies the requirements for multivariate normality. Two out of the four variables meet the assumptions for univariate normality, with the error rate deviating slightly and system usability deviating significantly from a normal distribution. Therefore, analysis will continue as planned with the caveat that caution should be applied when interpreting these two factors, particularly system usability, and only a particularly large difference should be considered significant.

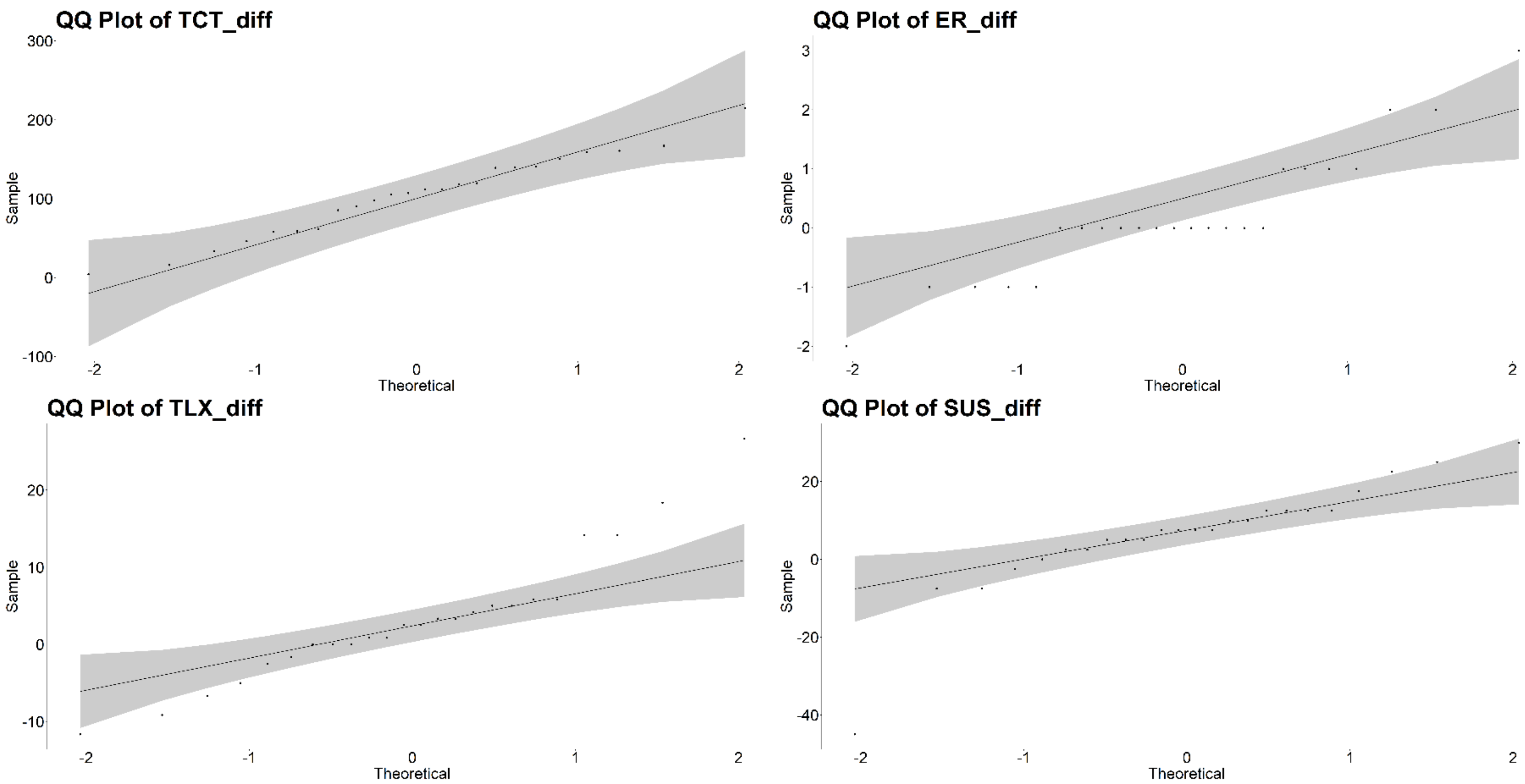


Chart 6.2 – Q-Q Plot to test for normality across all 4 dependent variables

6.3.2 Results of Trial 1

Though the primary aim of this study is to compare user performance between different variations of AR instructions, it is also worth noting some key differences between the baseline using paper instructions and AR as a whole. In this section, comparisons are made using the four performance measures identified in Section 4.2:

- ***NASA-TLX*** *(a measure of cognitive effort associated with a task)*
- ***ER*** *(error rate)*
- ***TCT*** *(total task completion time)*
- ***SUS*** *(system usability score, a quick way of for evaluating ease of use in industrial systems)*

Table 6.5 summarises the descriptive statistics of the collected data – i.e., the means and standard deviations for each performance measure and instruction type.

Table 6.5 – Overall mean and standard deviation of performance measures

	TLX		**ER**		**TCT**		**SUS**	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Paper	9.56	4.82	0.292	0.611	52.9	18.4	36.7	3.05
AR	11.1	6.11	0.5	0.816	157	44.0	39.0	2.64

Participants completed the task 56% faster when using paper instructions and rated them lower on the NASA-TLX scale. AR instructions meanwhile scored more highly on the System Usability Scale. There were very few errors made in either condition, and the differences in error rate are not considered noteworthy. Chart 6.3 shows the spread of results. Initial visual inspection of these data shows that the distribution of NASA-TLX scores is similar between AR and paper conditions, but AR had a peak of users who rated it much more highly than the paper instructions.

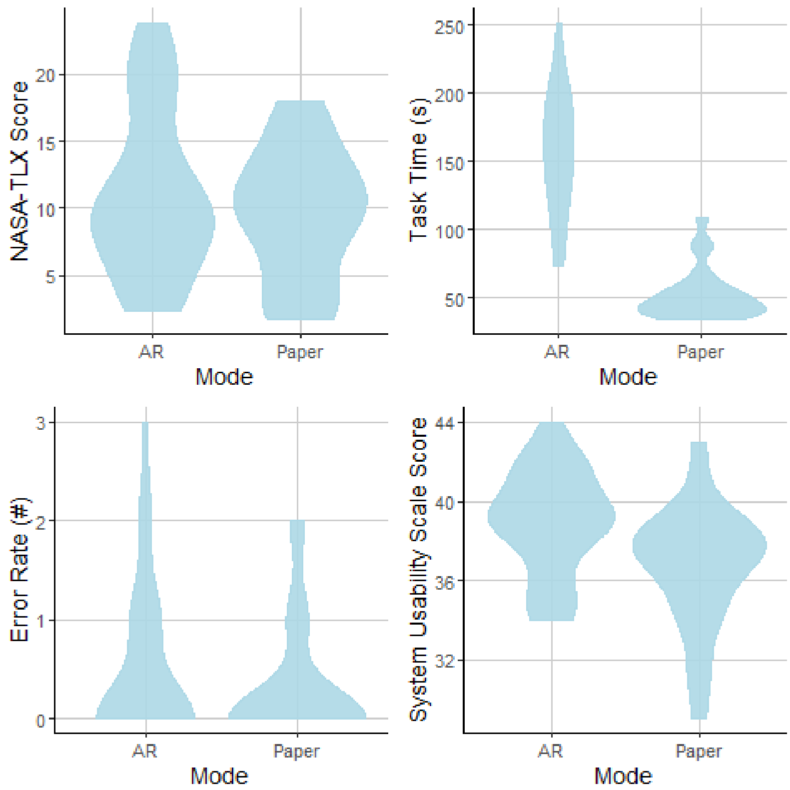
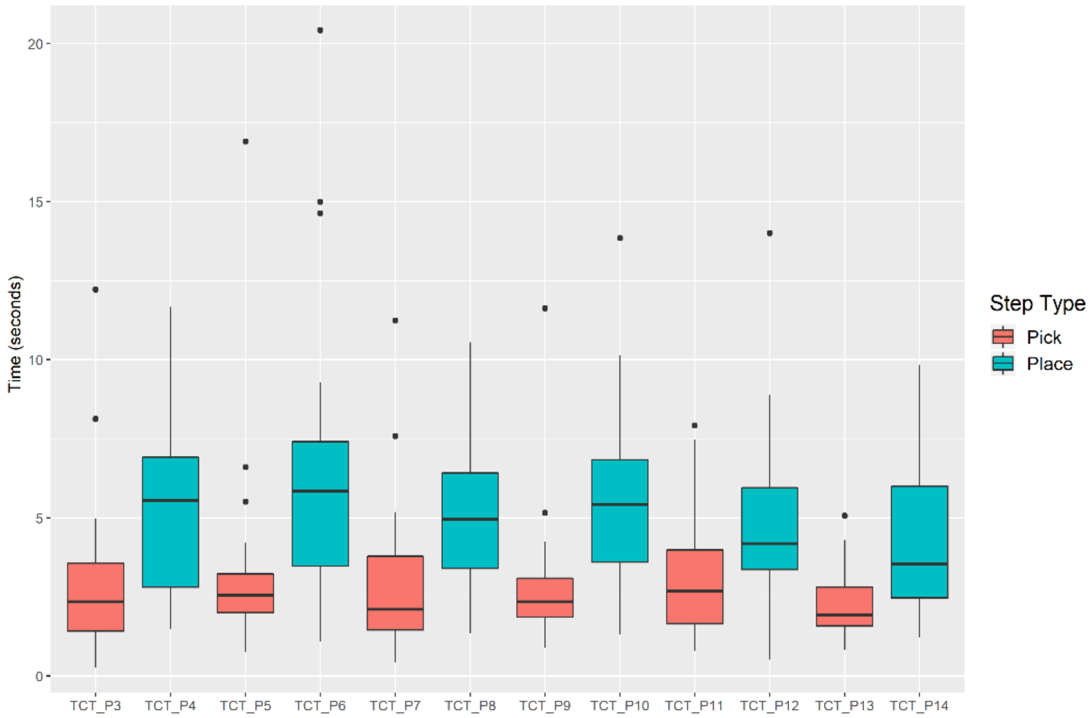


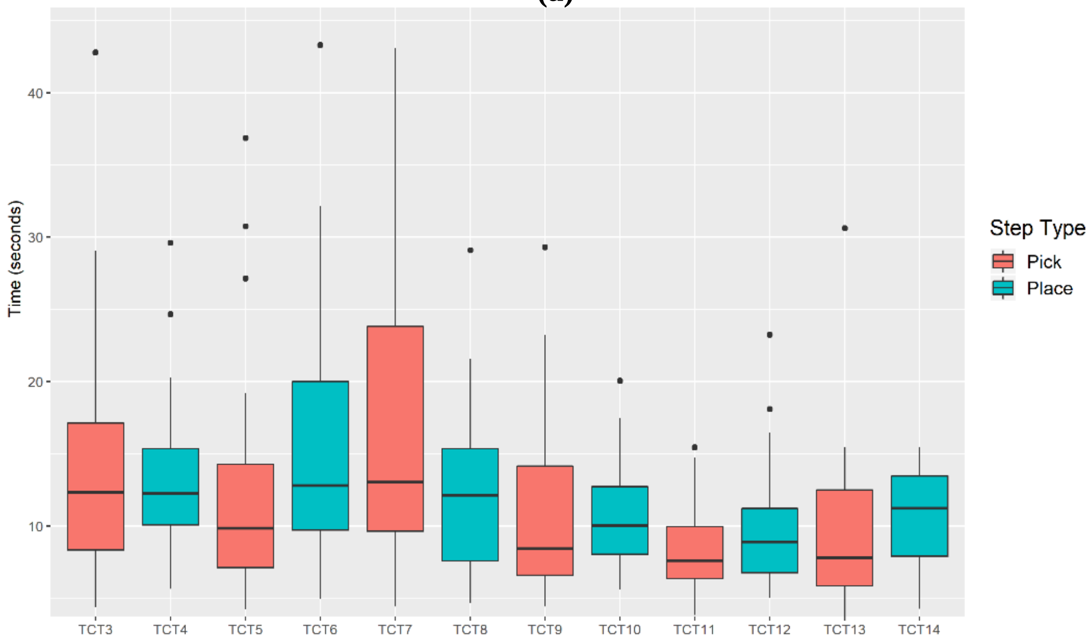
Chart 6.3 – Violin plot comparing all four dependent variables against instruction mode (Paper or Mobile AR)

Conversely, participants not only completed the task faster when using paper instructions than AR, they also performed much more consistently. Error rate appears similar for both conditions. System usability shows a similar shape of distribution for both AR and paper instructions, but AR scores more highly overall, whereas paper instruction has a heavier tail of participants who rated it poorly on usability.

Chart 6.4 (pg. 125) compares the time taken for each step of the assembly process, using both paper-based and mobile AR instructions. AR (Chart 6.4 *(b)*) clearly results in a longer time taken for each step, with seemingly random variation in the length of individual task steps. Paper (Chart 6.4 *(a)*) however shows a clear alternating pattern between the steps.



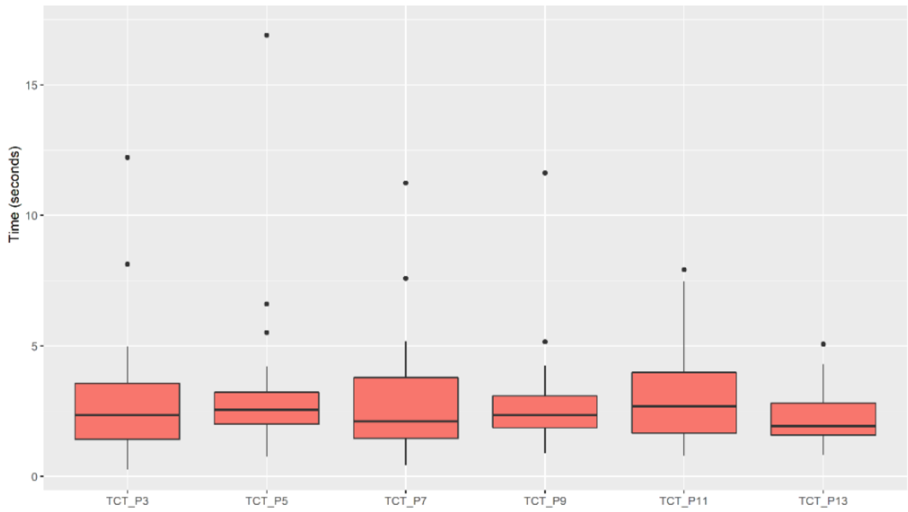
(a)



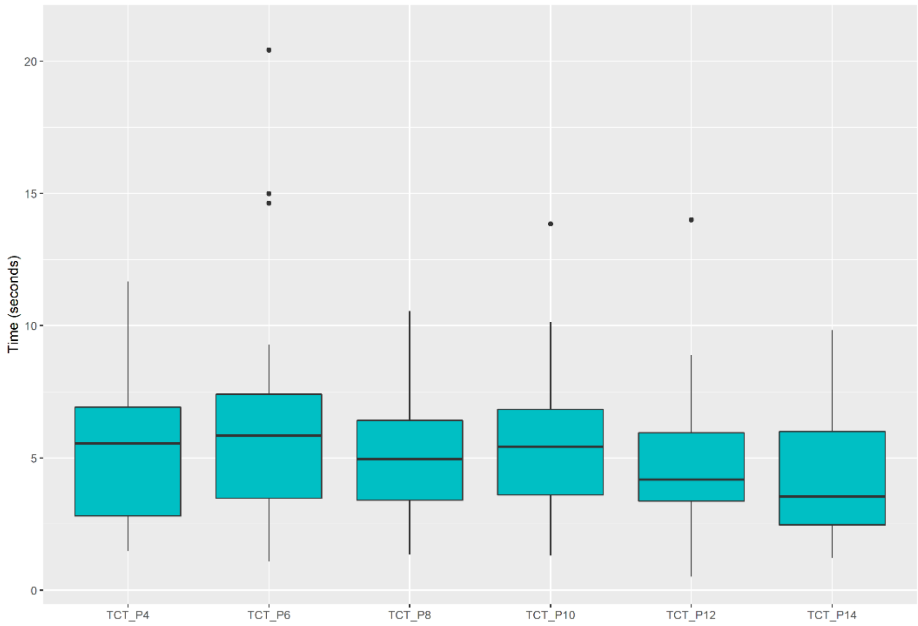
(b)

Chart 6.4 - Boxplot showing times taken to complete each step in the task using (a) paper instructions, and (b) mobile AR instructions

In Chart 6.5 (pg 126), the steps of the assembly task using paper-based instructions were separated into *(a)* 'pick' steps (locating and selecting the brick as indicated by the instructions) and *(b)* 'place' steps (assembling the chosen brick in the correct location).



(a)



(b)

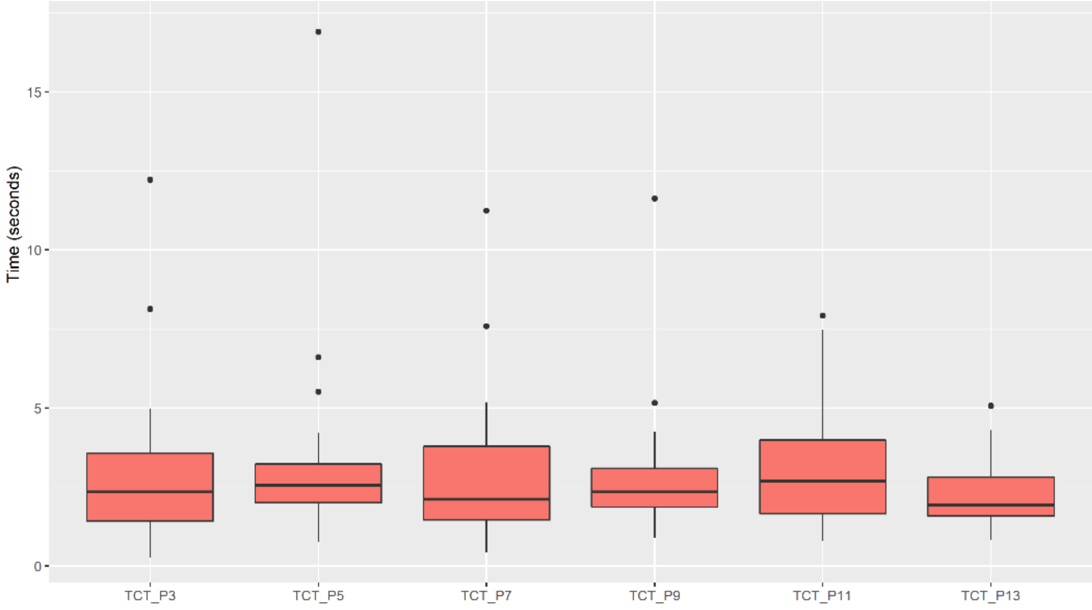
Chart 6.5 - Boxplot showing times taken for participants to complete each *(a)* 'pick' step and *(b)* 'place' step in the task using paper instructions

'Pick' steps take an average of 59% longer (Table 6.6) when using paper instructions.

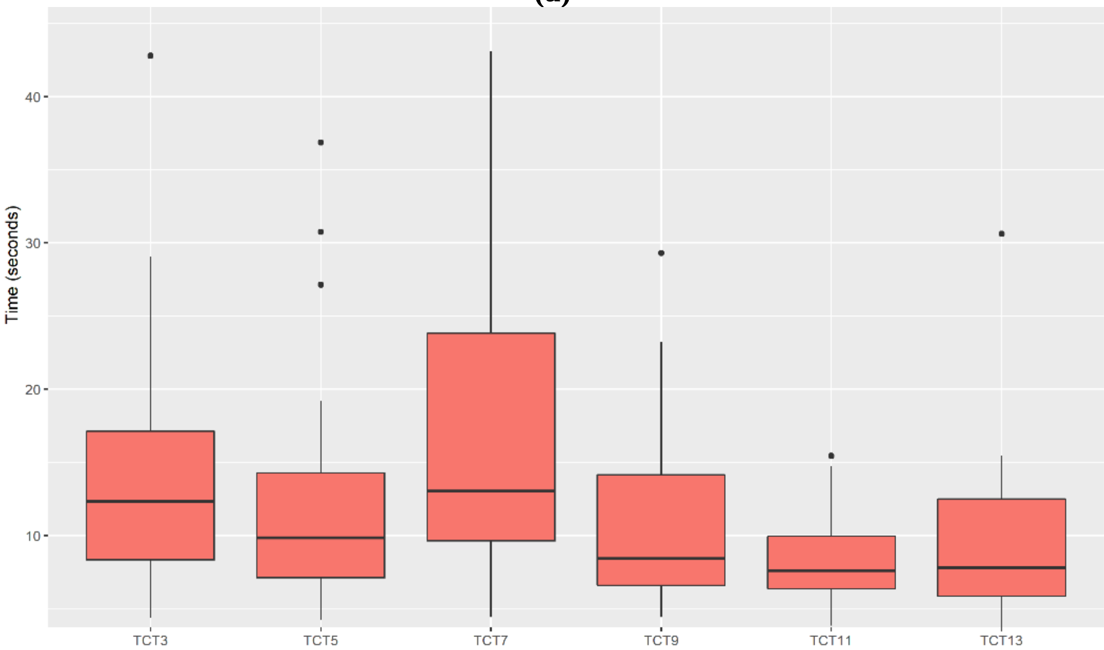
Table 6.6 – Average time for assembly steps

	'Pick' time (s)	**'Place' time (s)**
Paper	5.41	3.40
AR	13.1	13.1

Conversely, AR instructions appear to show no significant difference between 'pick' and 'place' phases of the assembly operation (Chart 6.4 (b) and Chart 6.6).



(a)



(b)

Chart 6.6 - Boxplot showing times taken to complete each (a) 'pick' step using paper instructions and (b) 'pick' step using mobile AR instructions

With paper instructions, performance is slower during the locating (‘pick’) phase of the instruction, while AR instructions, though considerably slower overall, show no such difference between the task steps. If performance with AR instructions is impacted by a lack of familiarity with technology, then it is possible that once users are acclimatised to AR usage, potentially both the pick and place steps will improve equally. Chapter 7 investigates this hypothesis further.

An overview of task progress and errors are presented in Chart 6.7 and Chart 6.8 (pg. 129 - 130). The charts show time step data for how participants progressed through the instructions for each instruction type, and clearly demonstrate where errors occurred and if they were corrected. However, it should again be noted that in the AR condition, some errors were corrected without stepping back through the instructions and therefore these will not appear in the charts below. Instead, these were recorded by observation.

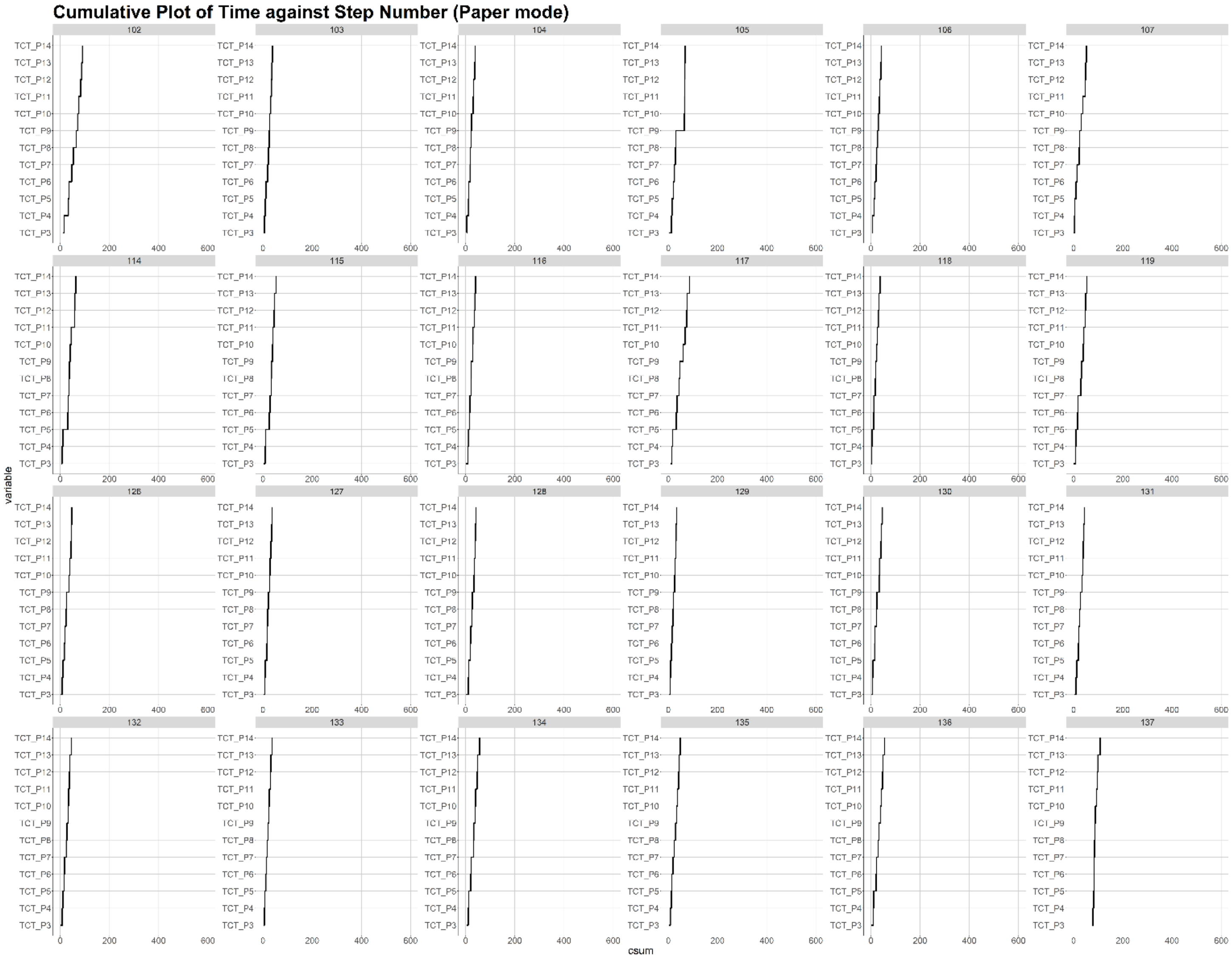


Chart 6.7 –Time series of step number against cumulative time taken to complete task using paper-based instructions

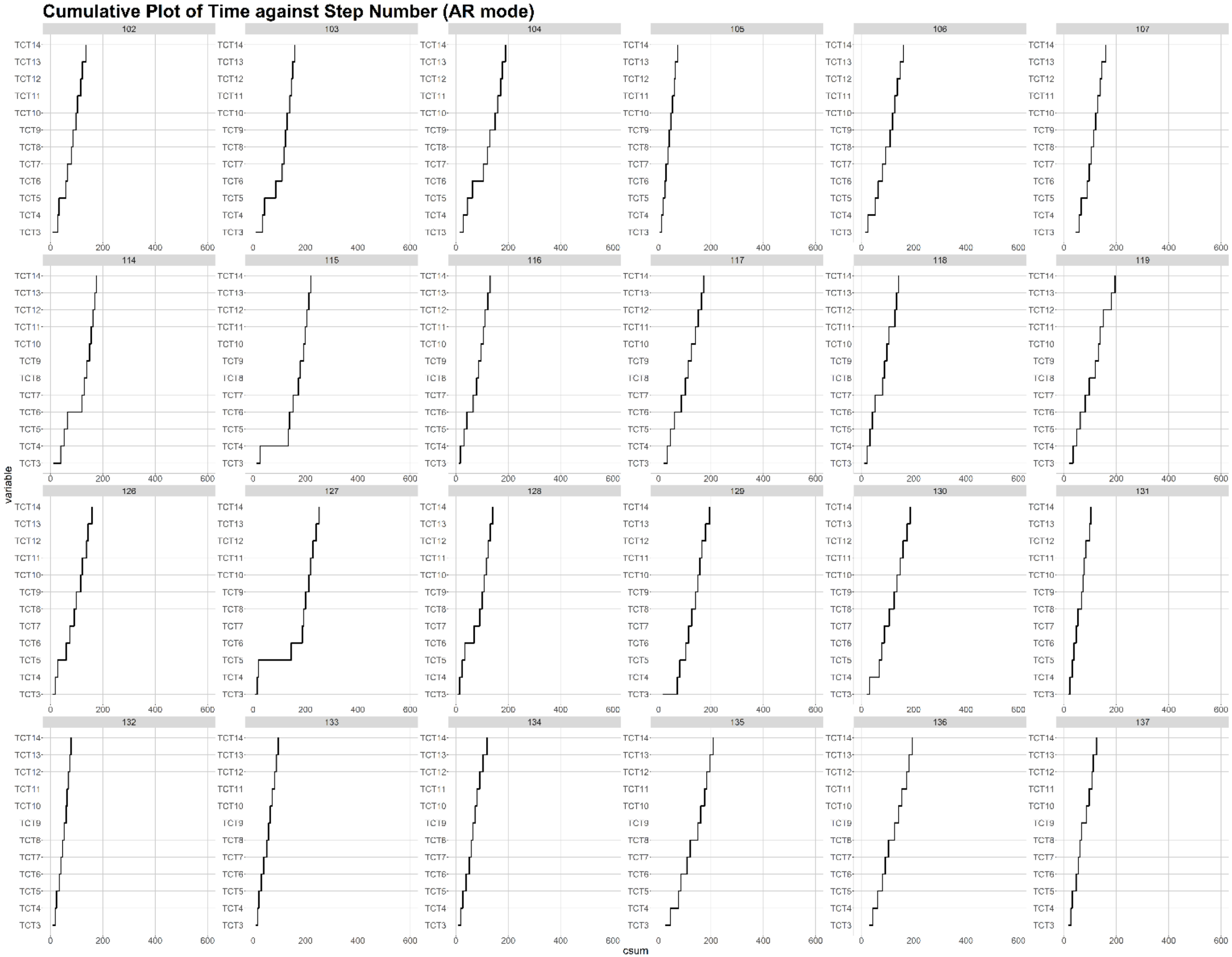


Chart 6.8 – Time series of step number against cumulative time taken to complete task using mobile AR instructions

The values presented in Table 6.6 and graphed in Chart 6.7 and Chart 6.8 (pgs. 129, 130) are calculated based on raw values measured. From this point onwards (Sections 6.3.2.1 - 6.5), values presented will be delta (Δ) values, as explained in Section 5.3, i.e., the difference between the user's performance using paper instructions and using AR instructions. For example, a larger (positive) delta value for TLX would indicate that the TLX score was higher under the AR condition than when using paper instructions, therefore more difficult to use. Correspondingly, a smaller (or negative) ΔTLX would indicate that AR was required less cognitive effort to use. Table 6.7 shows interpretation for a range of possible values for all four of the measured variables.

Table 6.7 – Interpreting the delta values in experimental results – AR versus paper instructions

	Positive value	**Zero**	**Negative value**
ΔTLX	This option required more cognitive effort for AR than paper on average	No difference	This option required less cognitive effort for AR than paper on average
ΔER	This option resulted in more errors for AR than paper on average	No difference	This option resulted in fewer errors for AR than paper on average
ΔTCT	This option took longer to complete the task for AR than paper on average	No difference	This option took a shorter time to completed for AR than paper on average
ΔSUS	This option was rated as more usable on average for AR than paper instructions	No difference	This option was rated as less usable on average for AR than paper instructions

6.3.2.1 Display Mode

Table 6.8 details findings for each of the three display modes tested against all four dependent variables.

Table 6.8 – Mean and standard deviation of each performance measure by display mode

	ΔTLX		ΔER		ΔTCT		ΔSUS	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
cad	2.50	10.3	-0.125	0.641	107	49.3	7.50	8.76
text	6.98	9.07	0.875	1.36	133	45.7	12.2	10.8
video	0.000	4.71	-0.125	0.991	72.0	46.1	-0.625	19.4

While a simple comparison of means might suggest some differences in performance based on display mode, further investigation was required. A MANOVA analysis was performed on this data to explore if any significant differences existed amongst the display types. Table 6.9 shows the resulting **p values** (the probability this result would have occurred without any differences in underlying populations) for the test and highlights any results that are deemed significant with more than 90% confidence.

Table 6.9 – MANOVA test for significant differences between different conditions for each of the dependent variables

	TLX	ER	TCT	SUS
Display	0.264 Not significant	0.108 Not significant	0.0533 Significant at the 90% level	0.194 Not significant

It reveals that the only performance factor majorly affected by the mode of displaying content to the user is Task Completion Time (TCT). By plotting this data as a boxplot (Chart 6.9, pg. 133), visual inspection can discern that in-situ video results in the shortest task time, followed at some distance by 3D models and then closely by text-based annotations.

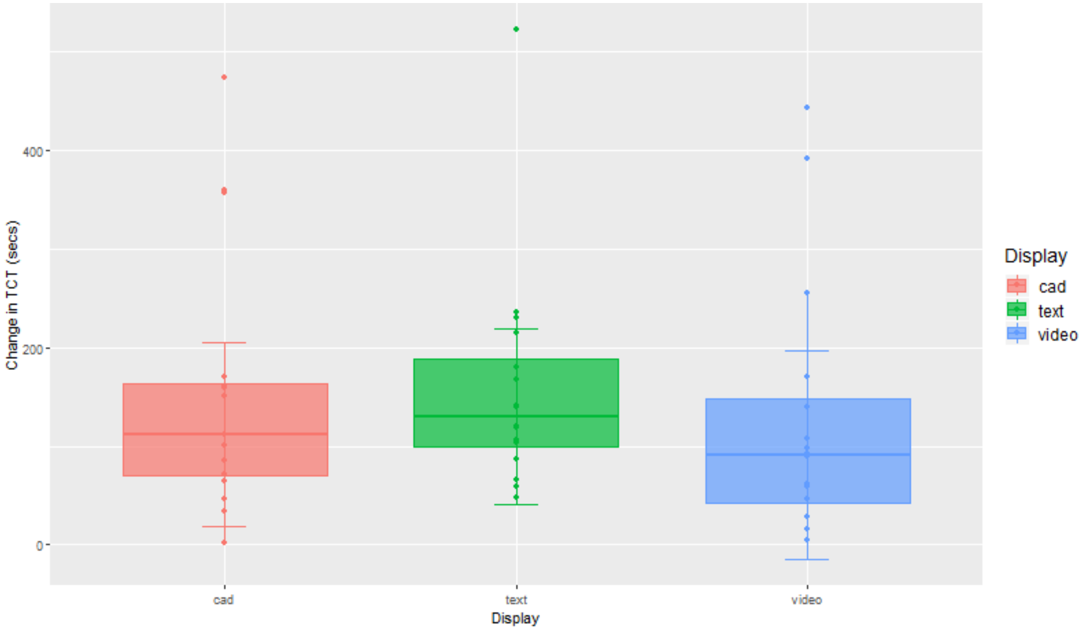


Chart 6.9 - Boxplot, dotplot and IQR of Display Mode against ΔTask Completion Time

To investigate this further, post-hoc testing was required. Tukey's HSD post-hoc analysis indicates a significant difference between video and text based annotations, with a p value of less than 0.05, indicating 95% confidence that the difference truly exists and is not just down to random variation (Table 6.10).

Table 6.10 – Output of Tukey's HSD test

	diff	**lwr**	**upr**	**p adj**
text-cad	25.6	-32.8	84.0	0.515
video-cad	-35.4	-93.7	23.0	0.294
video-text	-61.0	-119	-2.60	0.0398

This implies that Device Type has a significant effect on AR assembly performance, when considering Task Completion Time as a key measure of success. Specifically, the use of in-situ videos appears to reduce Task Completion Time significantly when compared to AR instructions delivered using text-based annotations.

Boxplots for the other three factors (Task Load Index, Error Rate, and System Usability) are presented for consideration. None of the differences indicated are considered statistically significant, so care should be taken in using these results, however they are presented here as in the absence of any other factors affecting the choice of display mode, perhaps these marginal differences may act as a tie breaker.

Chart 6.10 shows very small differences in terms of cognitive load, suggesting a marginal benefit to using in-situ videos may exist. However, the differences are small in comparison to the variation within each display mode, and so should not be considered statistically significant.

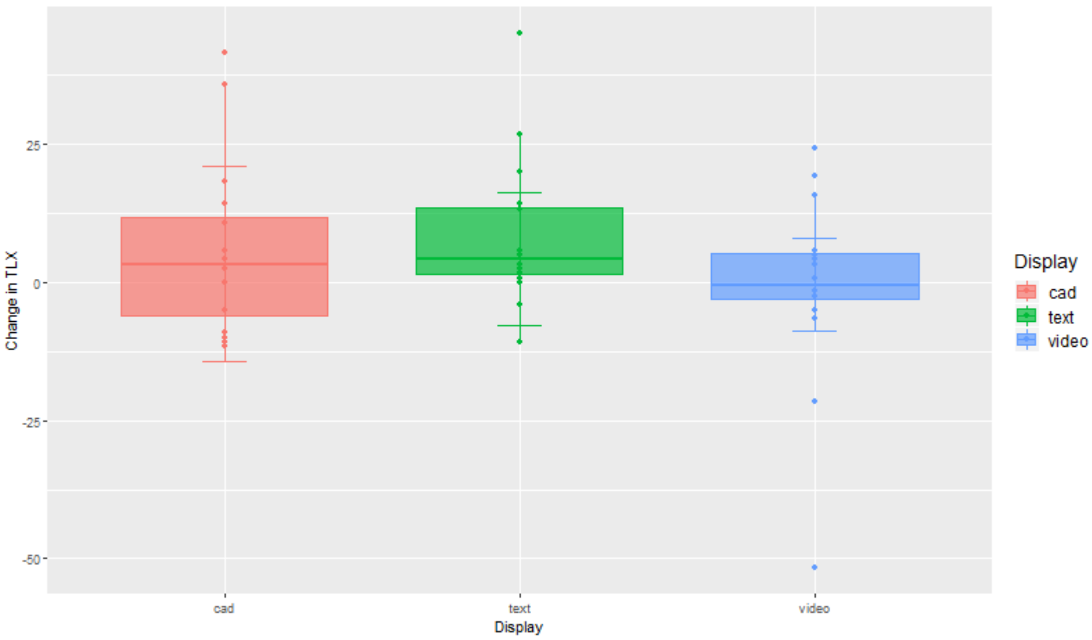


Chart 6.10 – Boxplot, dotplot and IQR of Display Mode against ΔTask Load Index

Although Chart 6.11 (pg. 135) shows the error rate for the ‘annotation’ display mode has far more variation than either video or 3D models, there are very few errors in any of the conditions, and the data are not normally distributed, so this is not significant.

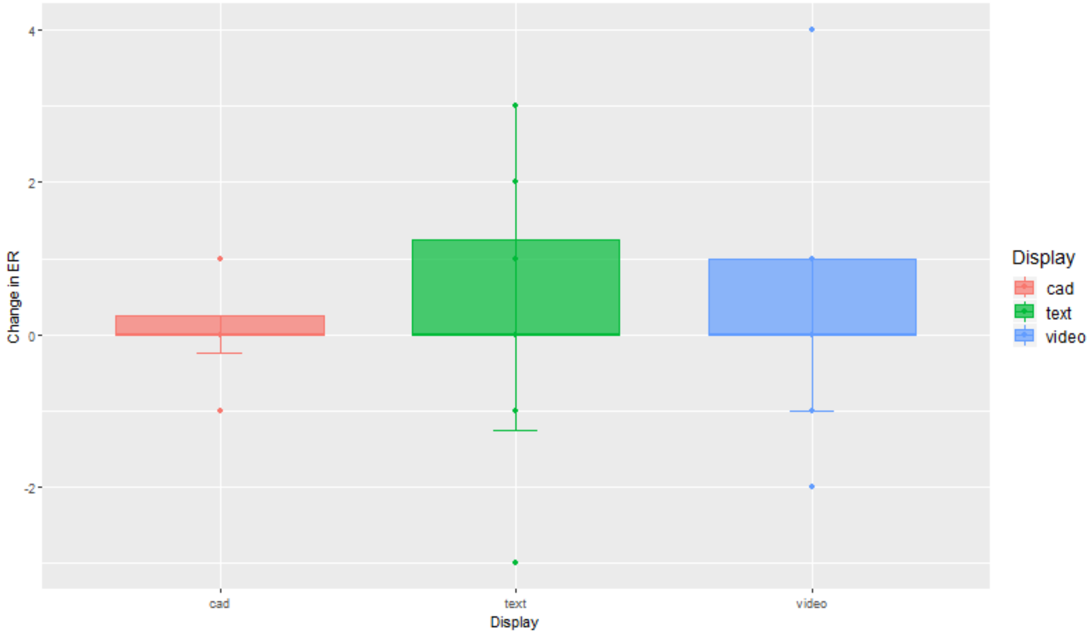


Chart 6.11 - Boxplot, dotplot and IQR of Display Mode against ΔError Rate

The boxplot for usability (Chart 6.12) shows only minor variation between the conditions. This combined with the abnormality of the data and the findings of the MANOVA analysis suggest these results should not be regarded as important.

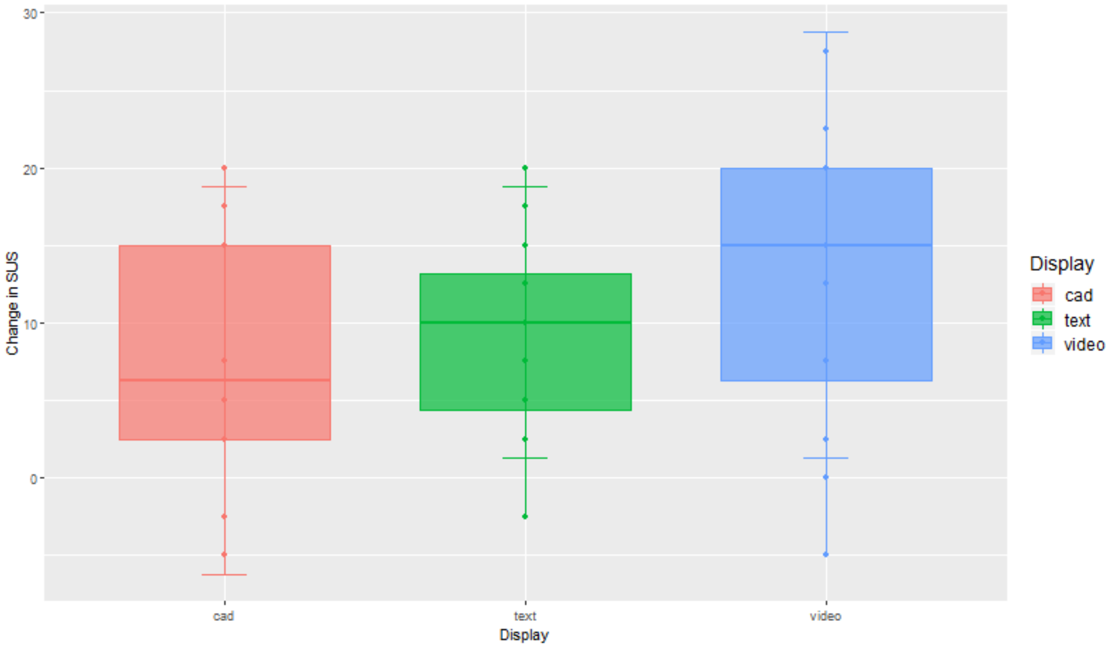


Chart 6.12 - Boxplot, dotplot and IQR of Display Mode against ΔSystem Usability Scale

6.3.2.2 Interaction Method

Table 6.11 shows the mean and standard deviations for each of the four measured variables, when using both native interaction and voice control to direct the flow of instructions within the AR app.

Table 6.11 – Mean and standard deviation of performance measure by interaction method

	ΔTLX		ΔER		ΔTCT		ΔSUS	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Native	3.47	6.80	0.500	1.38	93.1	58.4	7.71	10.1
Voice	2.85	10.3	-0.0833	0.669	115	43.8	5.00	17.8

As before, a MANOVA analysis was required to determine if any significant differences exist between the groups considered. The analysis was carried out in accordance with the method described in Section 4.5.1. Table 6.12 (pg. 137) shows the results.

Table 6.12 – MANOVA test for significant differences between different conditions for each of the dependent variables

	TLX	ER	TCT	SUS
Interaction	0.862 Not significant	0.202 Not significant	0.309 Not significant	0.651 Not significant

Against a threshold value of 95% confidence, the interaction method was not considered to make a statistically significant difference to any of the measured variables. However, the TLX score would be considered significant if the confidence level was lowered to 85%. There is an 85% or higher chance that the TLX score is affected by the type of interaction method used (Chart 6.13, pg. 137). This is notably below the typical threshold value of 95%, so the importance of this result should not be overstated. However, perhaps in the situation where no other factors exist to influence the decision, the fact that Voice Commands did result in a slightly lower mean Task Load Index (by visual inspection of Chart 6.13) may be taken into consideration.

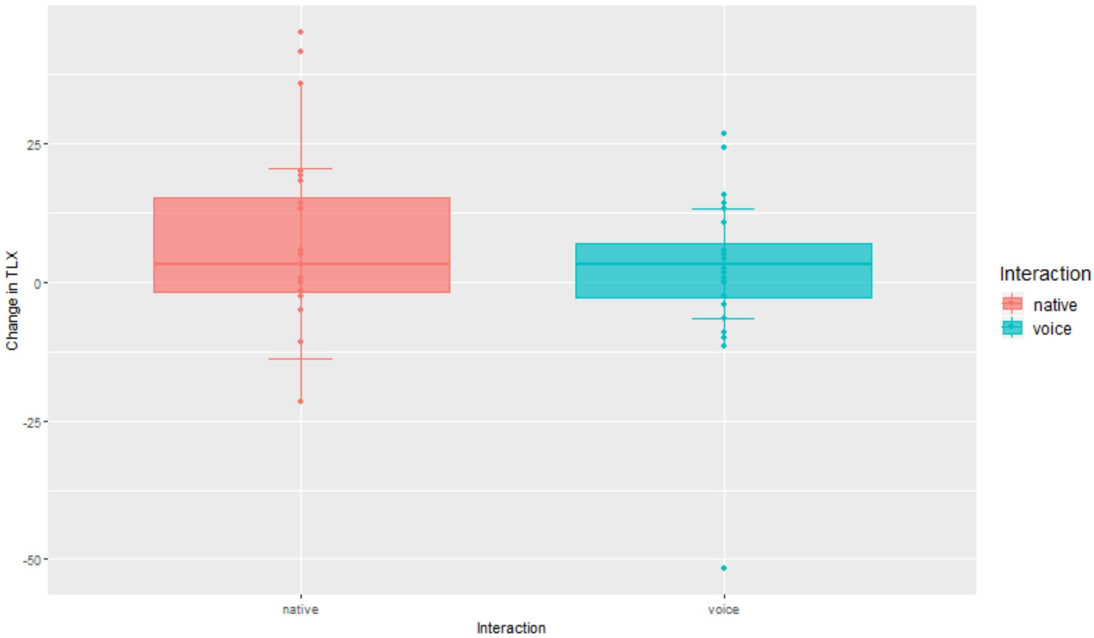


Chart 6.13 – Boxplot, dotplot and IQR of Interaction Method against ΔTask Load Index

6.3.3 Discussion

In Section 6.3, the results of a study to explore the effect of AR display mode on four key performance metrics are presented. From the data, in-situ videos result in fewer errors than either text-based annotations or 3D models. The video mode also resulted in faster task completion than the other options. Therefore, an in-situ video presented in the AR environment is recommended as the best use case for simple assemblies such as the one presented in this chapter.

At the start of Section 6.3.2, a disparity is noted between times taken for 'pick' steps vs 'place' steps when using paper instructions that does not exist when AR instructions are followed. While performance is generally lower when using AR than paper in this study, this is possibly due to a lack of familiarity with the technology. Therefore, this raises questions over whether the disparity between different phases of the assembly task may be reduced if overall performance improves once AR is no longer a novelty. Though it could be argued that mobile phones themselves are a well-established technology, the use of mobile phones to display and interact with AR content is still a new concept to most consumers. Indeed 83% of participants in this study reported their experience with AR as being a level 2 or less on a scale of 1 to 5, where 1 is no experience at all, and 5 is expert user (Appendix C).

The outcome of Section 6.3.2.2 demonstrates that the method by which users control and interact with AR content appears to have no statistically significant impact on any of the measured variables. Therefore, this decision can safely be made on environmental factors of the workplace. For example, noisy work environments may be better suited to touchscreen buttons to control the flow of information, whereas voice commands may be more appropriate where users must wear PPE such as gloves, which may impede their use of a touchscreen device. If no such environmental factors exist in the workplace, then those implementing AR may wish to consider multimodal interaction, allowing users themselves to decide which method they prefer, while management can be confident that either choice will not negatively affect performance metrics.

6.4 Trial 2: Wearable AR

Following the results of the Mobile AR study in Section 6.3, a companion study was carried out to investigate assembly performance when guided by AR instructions delivered on wearable displays. In this case, the first-generation Microsoft HoloLens (Microsoft, 2021a) as shown in Figure 6.1.

Figure 6.1 –Microsoft HoloLens, 1st generation

As in 6.3, differences in performance were explored between different methods of displaying the content and different techniques for interacting with the instructions. As before, participants also completed a task guided by paper-based instructions, and the main performance measures considered were the delta (rather than raw) values. Later in the chapter, Section 6.5 combines both the datasets from Section 6.3 and this section (6.4.2) to determine whether device type has an effect on performance and to investigate any interaction between the different factors considered. However, this section focuses on analysing this study as a standalone dataset. In this study, participants are denoted by a 3-digit number starting with a 2 (i.e. 2XX) to indicate they were part of Trial 2.

6.4.1 Assumptions

Both Task Completion Time (TCT) and System Usability Score (SUS) are non-leptokurtic (Table 6.13).

Table 6.13 – Tests for Normality on each individual performance measure

Variable	Skewness	Kurtosis	Shapiro-Wilks Test
TCT	0.754897 moderately skewed	2.27441 platykurtic	0.011031 significant deviation
ER	0.098939 approx. symmetric	6.489507 leptokurtic	0.000514 significant deviation
TLX	-0.4025 approx. symmetric	4.096405 leptokurtic	0.365365 approx. normal
SUS	-0.44868 approx. symmetric	2.711865 mesokurtic	0.627319 approx. normal

However as stated previously (Section 4.5.1) the MANOVA test is robust to deviations from normality in terms of kurtosis, so this is not of major concern. Task Completion time is also moderately skewed and scores poorly on the Shapiro-Wilks test, suggesting another analysis method may be better suited for this portion of the data. Error rate scores well for skewness and kurtosis, but the Shapiro-Wilks test suggests the data deviates from a normal distribution. Shapiro-Wilks is not always considered accurate at smaller sample sizes, so given the good score for skewness and kurtosis, visual inspection of the data distributions will be used to decide if the data meets the assumptions required for MANOVA. TLX and System Usability both score well on the Shapiro-Wilks test, and though System Usability does fall below the threshold value of 3 for kurtosis, at 2.71, it is close to the threshold and scores well on the other metrics. This makes it a viable candidate for MANOVA analysis.

As stated previously, visual inspection of the univariate distributions will be used to decide if MANOVA is an appropriate method of analysis for Error Rate. In the curve shown on Chart 6.14, the data roughly follow the shape of a normal curve. However, caution will be applied when interpreting the results of this analysis and only large changes in performance should be treated as particularly significant.

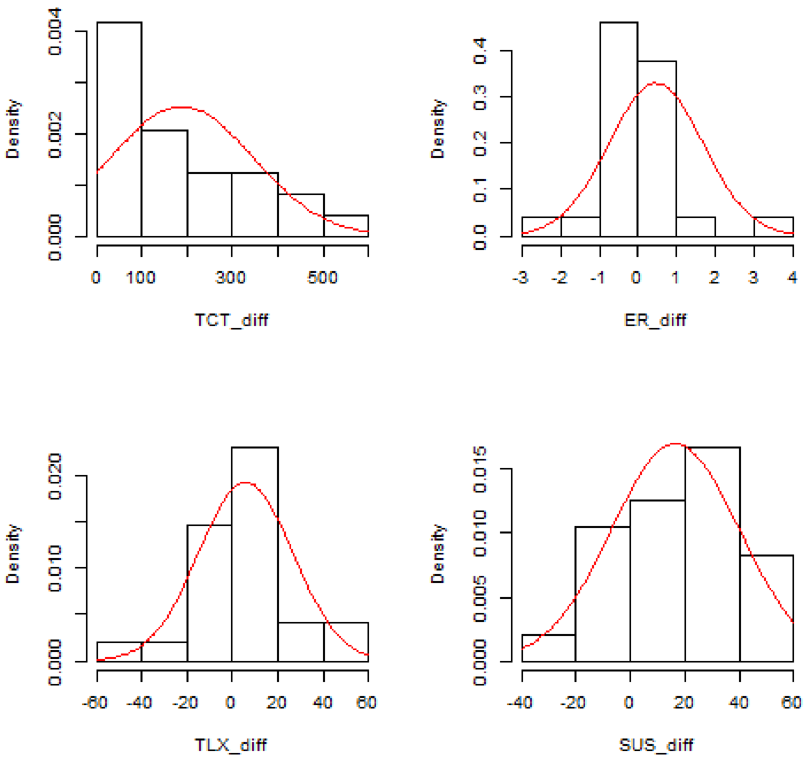


Chart 6.14 - Histograms showing univariate distributions of each dependent variable

Chart 6.15 (pg. 144) shows a QQ-plot of all four variables. Most points lie within the shaded grey area (which represents a 95% confidence interval), so based on this, the data appears to demonstrate multivariate normality. However, given the obvious departure from normality shown by Task Completion Time in Chart 6.14, this factor does not appear to meet the requirement of normality and so it is not appropriate to use MANOVA to analyse this factor.

Error Rate, NASA-TLX score and System Usability will be analysed using MANOVA techniques, though some caution will be applied when interpreting results for Error Rate. Task Completion Time however fails to meet the assumptions required for MANOVA, and alternate methods of analysis must be sought. According to the plan for analysis laid out in Section 4.5.1, the Kruskal-Wallis non-parametric test may be used as an alternative to MANOVA. This was implemented using the R base function *kruskal.test()* (The R Foundation, 2021).

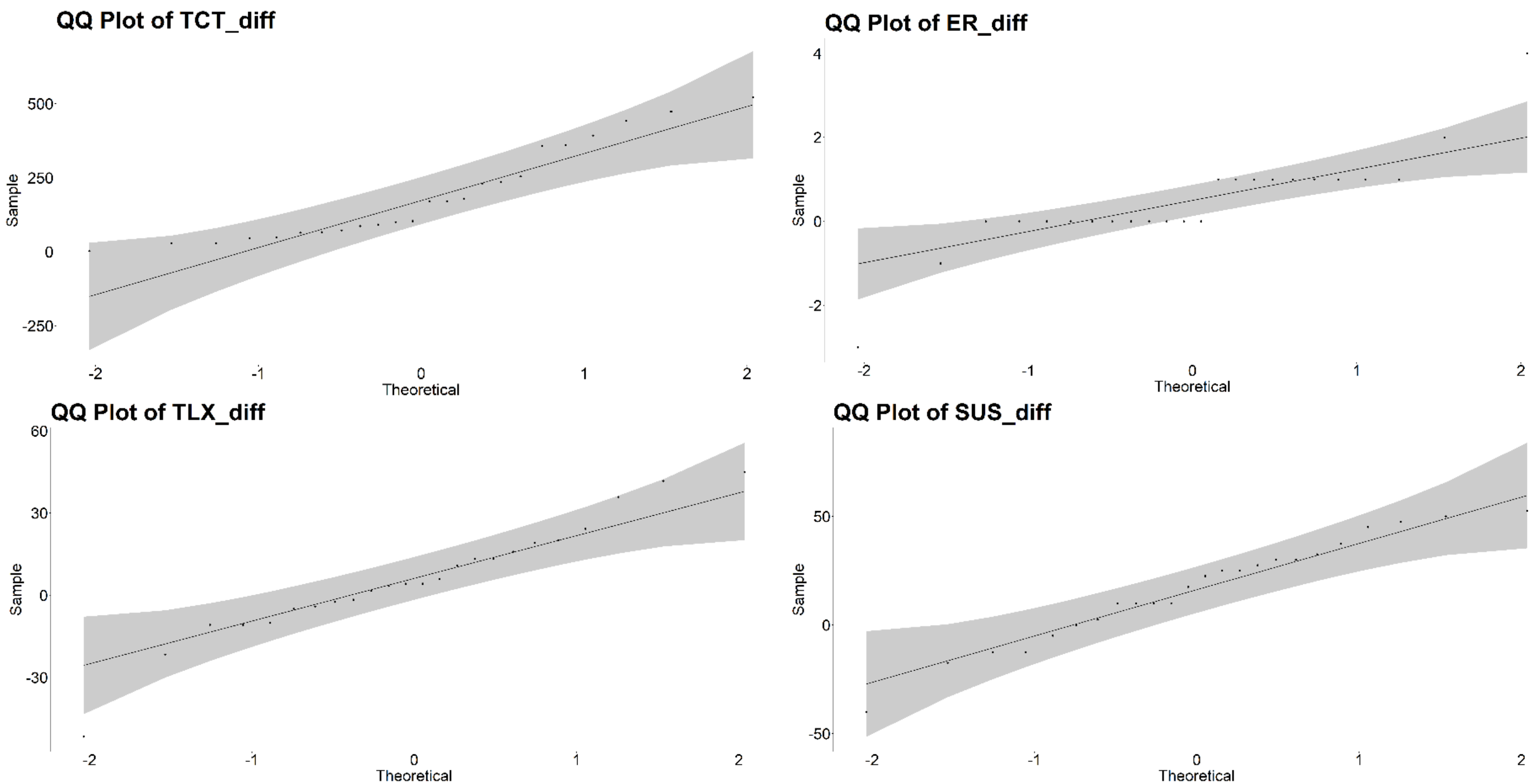


Chart 6.15 – Q-Q Plot to test for Normality across all four dependent variables

6.4.2 Results of Trial 2

First, comparisons were drawn between user performance when using the paper instructions versus use of Wearable AR devices overall, as summarised in Table 6.14.

Table 6.14 – Overall mean and standard deviation of each performance measure

	TLX		ER		TCT		SUS	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Paper	25.9	15.0	0.333	0.850	51.2	19.4	28.2	15.1
AR	31.7	14.6	0.792	1.15	240	154	44.8	15.7

Chart 6.16 (pg. 146) shows there is minimal difference between NASA-TLX and Error Rate scores between the AR and paper conditions. Task Time in contrast is much faster and much more consistent between participants when using paper instructions, while those using AR had a much more varied experience. System usability has quite an even spread of results for the AR condition, suggesting while some very much enjoyed the experience, others were more neutral or did not find the system usable. Paper instructions were more consistently rated poorly on usability score.

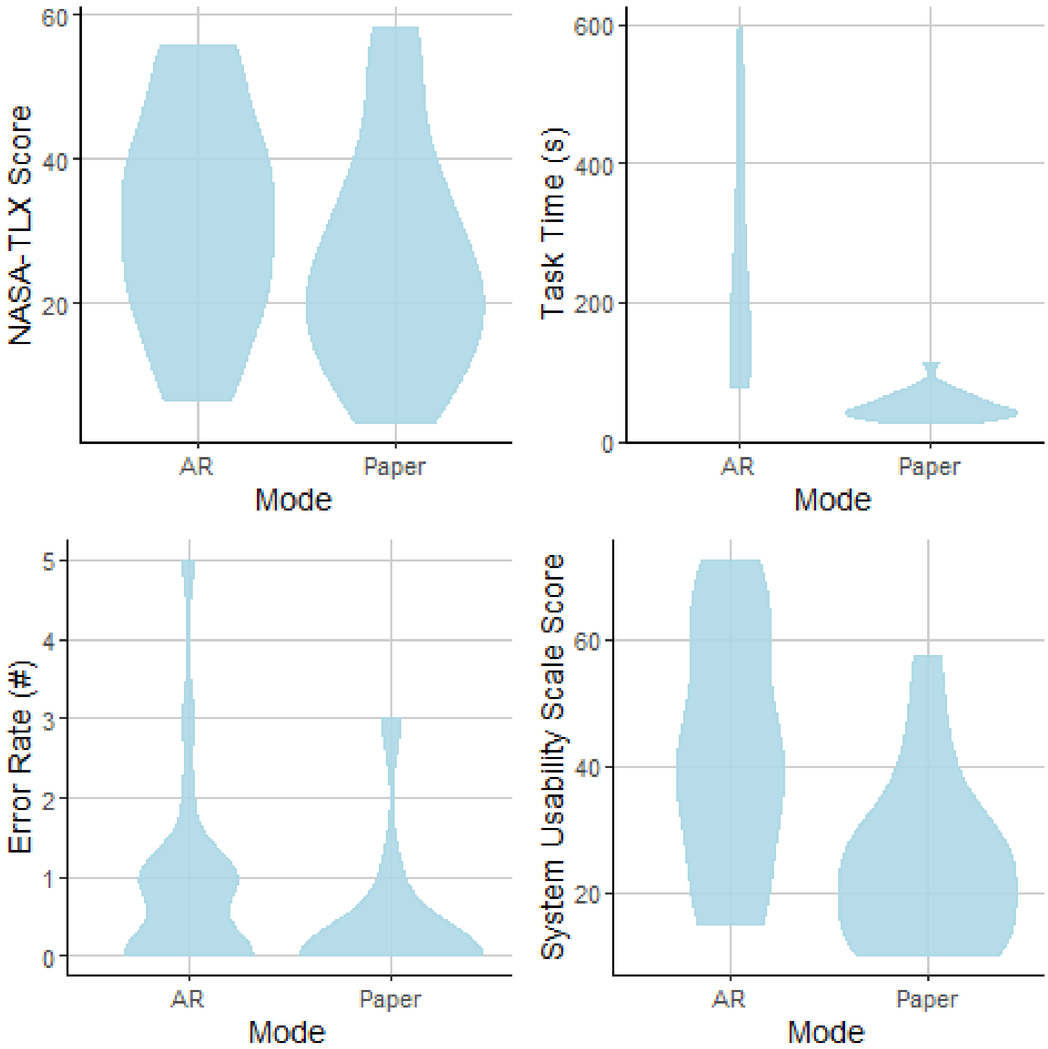
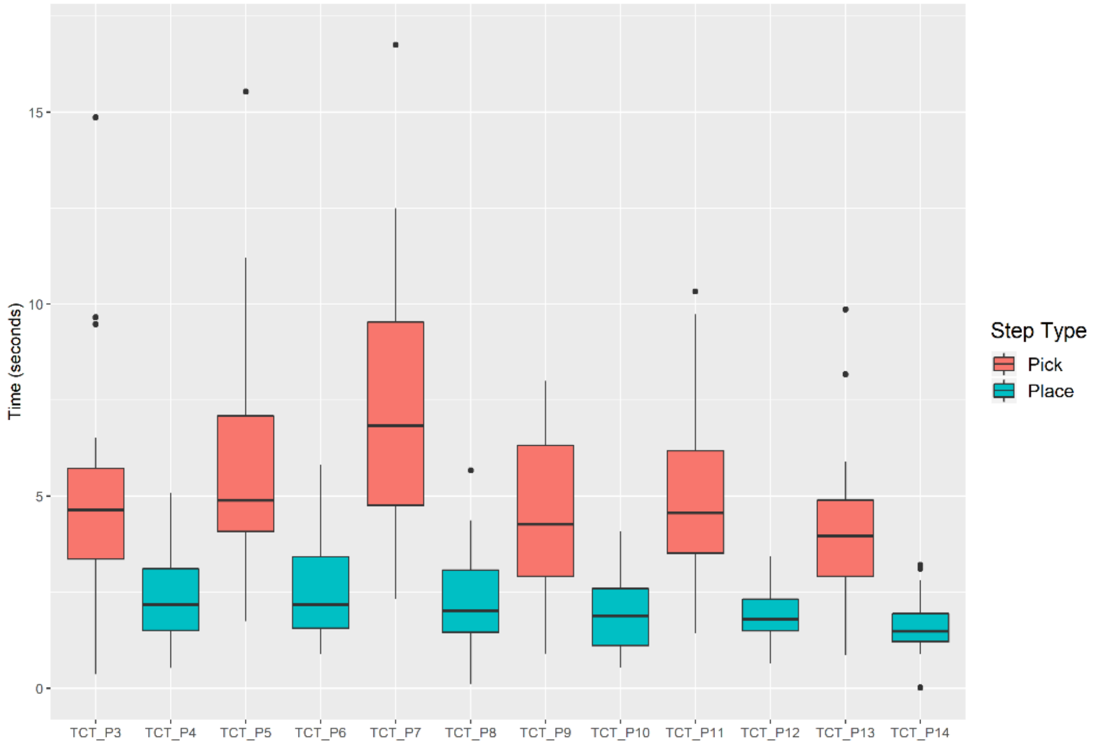
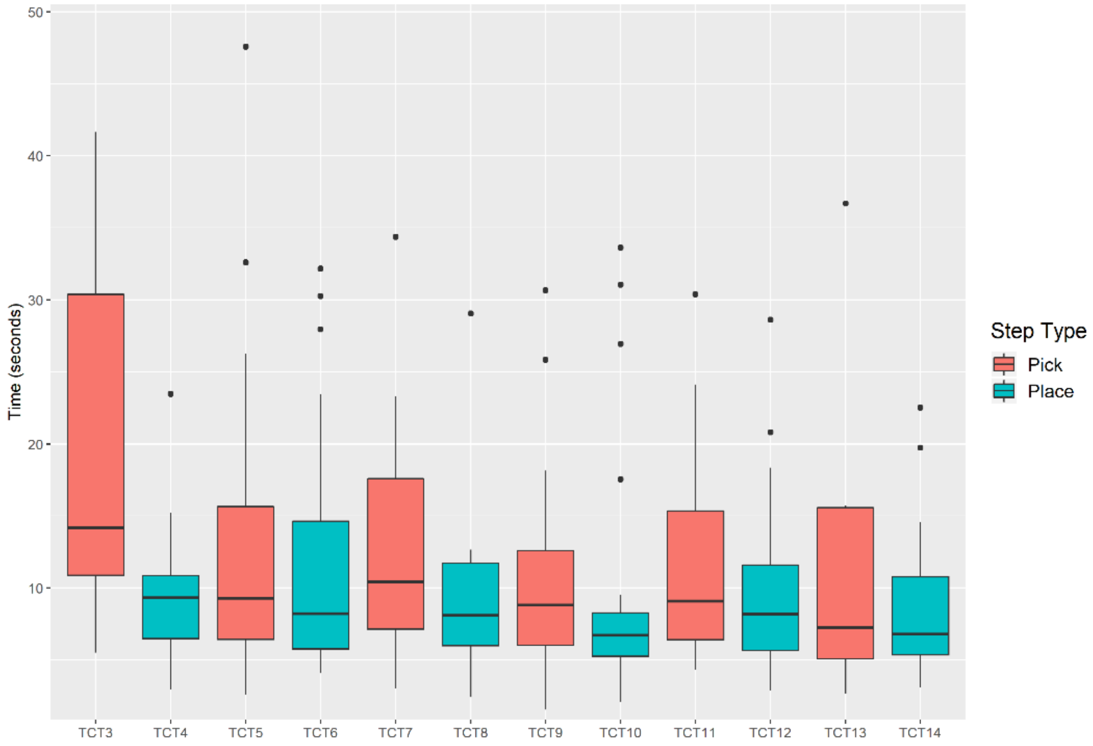


Chart 6.16 - Violin plot comparing all four dependent variables against instruction mode (Paper or Wearable AR)

Charts 6.17 – 6.19 (pg. 147 - 149) demonstrate a similar pattern to that in section 6.3.2 – that is, that paper instructions exhibit a clear difference in the time taken to locate and select a component, and the time taken to place that component in the desired location. Wearable AR instructions do not produce such an effect.

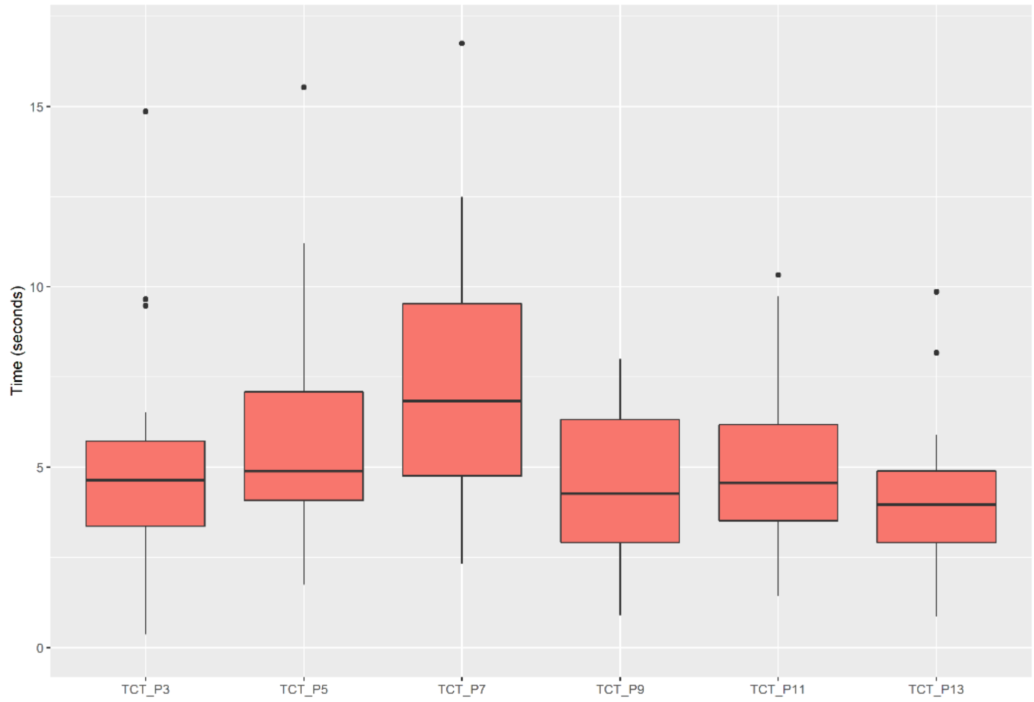


(a)

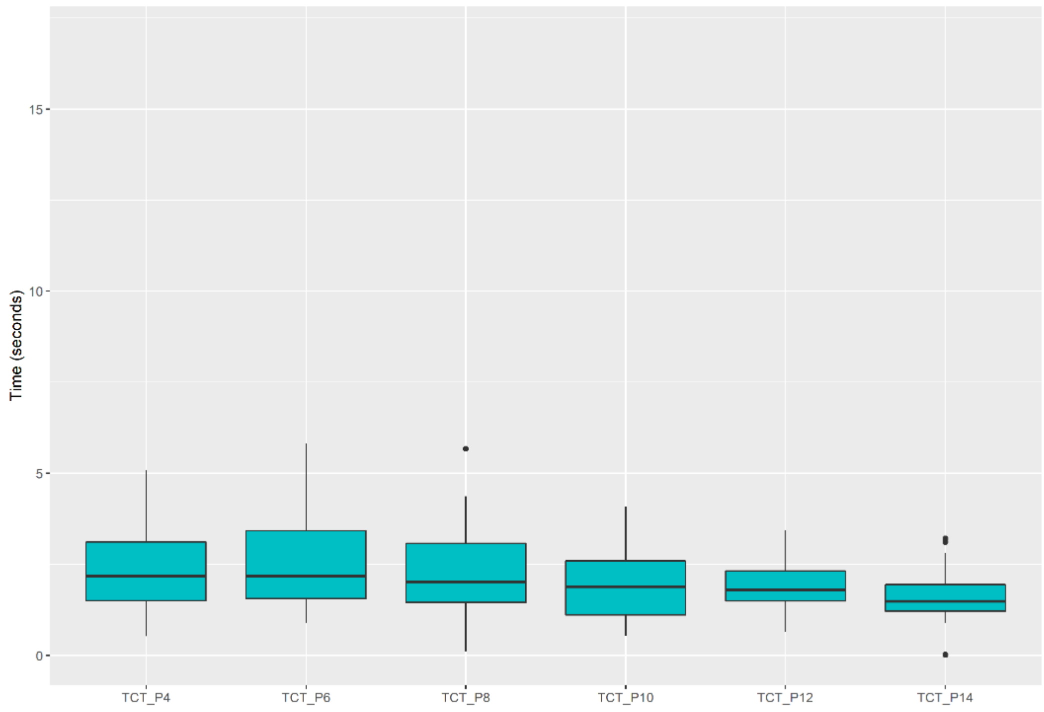


(b)

Chart 6.17 - Boxplot showing times taken for participants to complete each step in the task using (a) paper-based instructions, and (b) wearable AR instructions

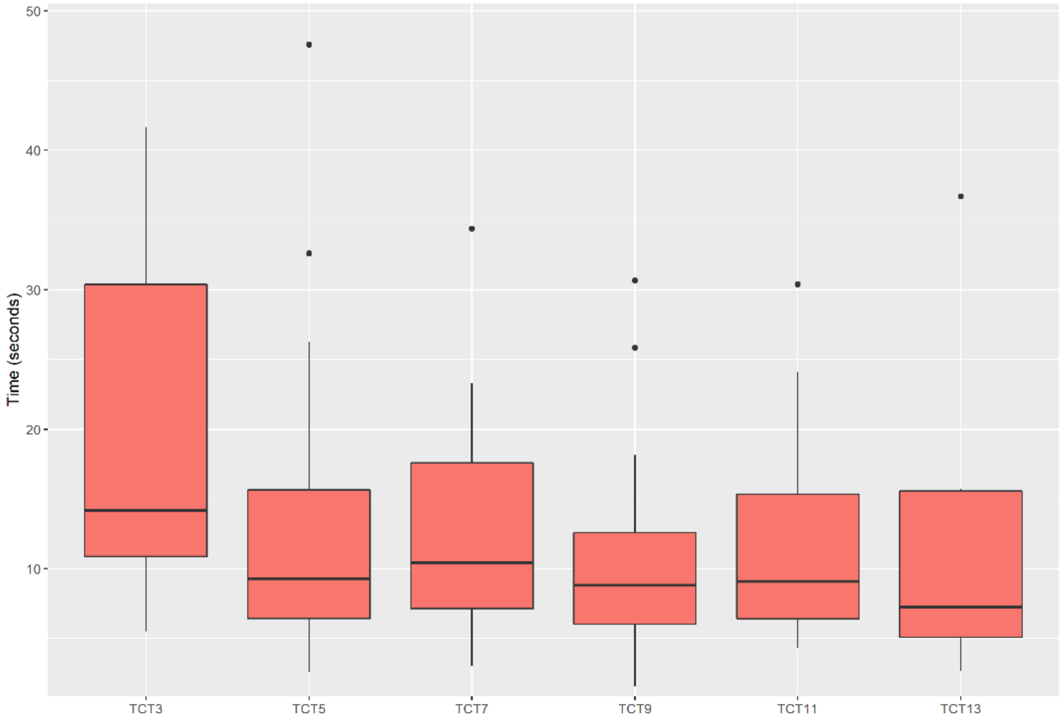


(a)

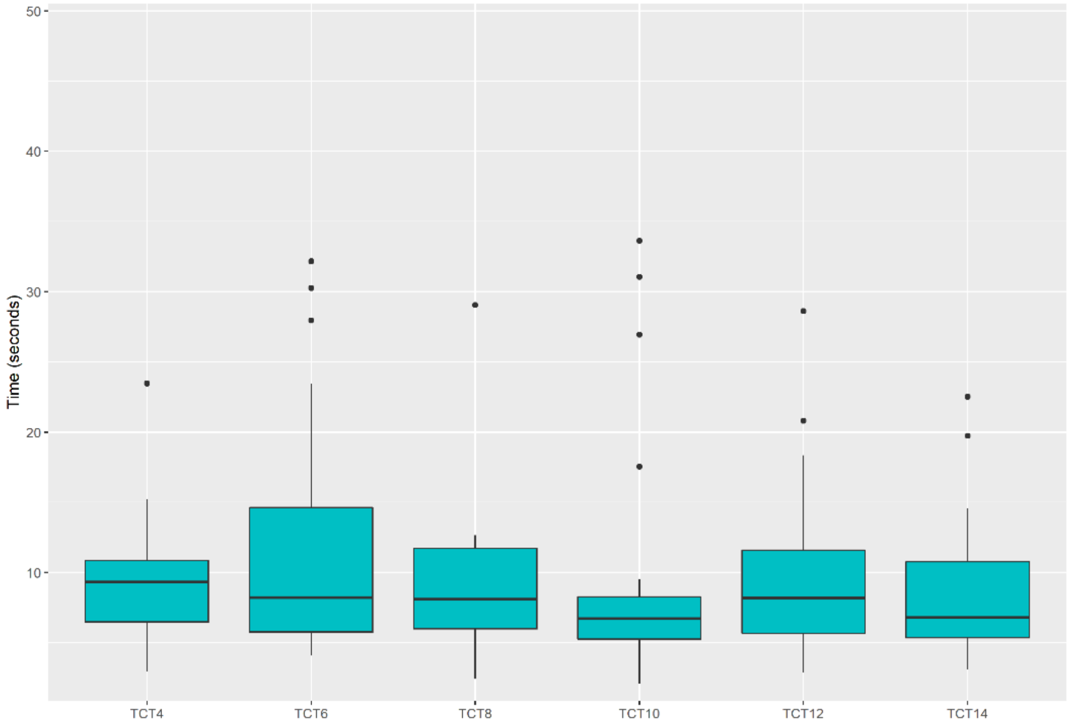


(b)

Chart 6.18- Boxplot showing times taken for participants to complete each (a) 'pick' step and (b) 'place' step in the task using paper-based instructions



(a)



(b)

Chart 6.19 - Boxplot showing times taken for participants to complete each (a) 'pick' step and (b) 'place' step in the task using wearable AR instructions

Next, the data is presented as cumulative time series plots, showing when users completed each step, and if they went back to correct errors. As in Section 6.3.2, it should be noted that this method of plotting does not capture uncorrected errors, or errors that were corrected without going backwards through the instructions. Chart 6.20 (pg. 151) shows the results for participants using paper instructions: the progression through the assembly steps is rapid with few pauses and errors. Though the mean task time for paper is around a quarter of that for Wearable AR, Chart 6.21 (pg. 152) shows that the majority of tasks completed using AR were also fast, but a few instances with large pauses mid-assembly (notably participants 208, 212, 241 and 247) are the driving cause for the increased total task time.

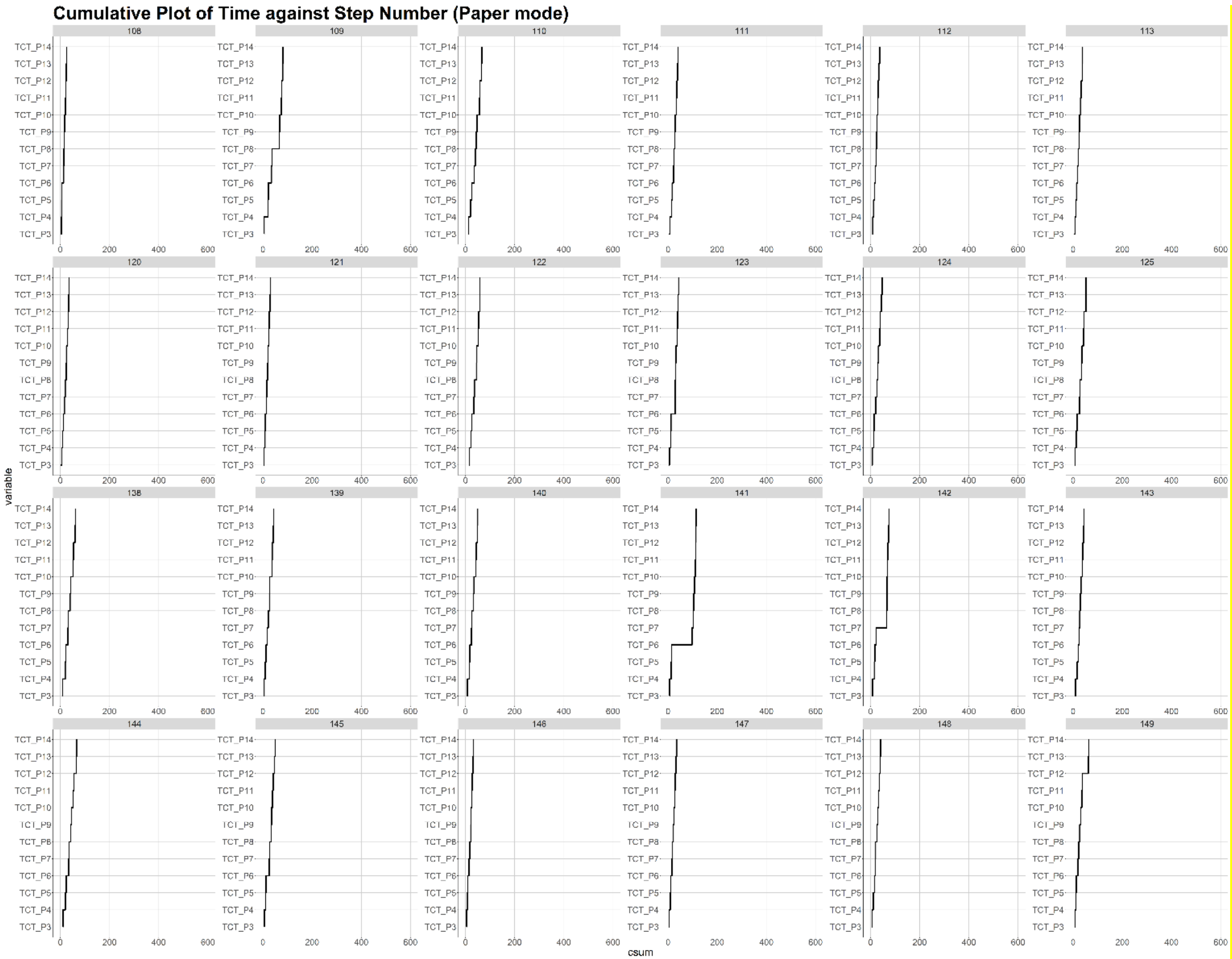


Chart 6.20 - Time series of step number against cumulative time taken to complete task using paper-based instruction

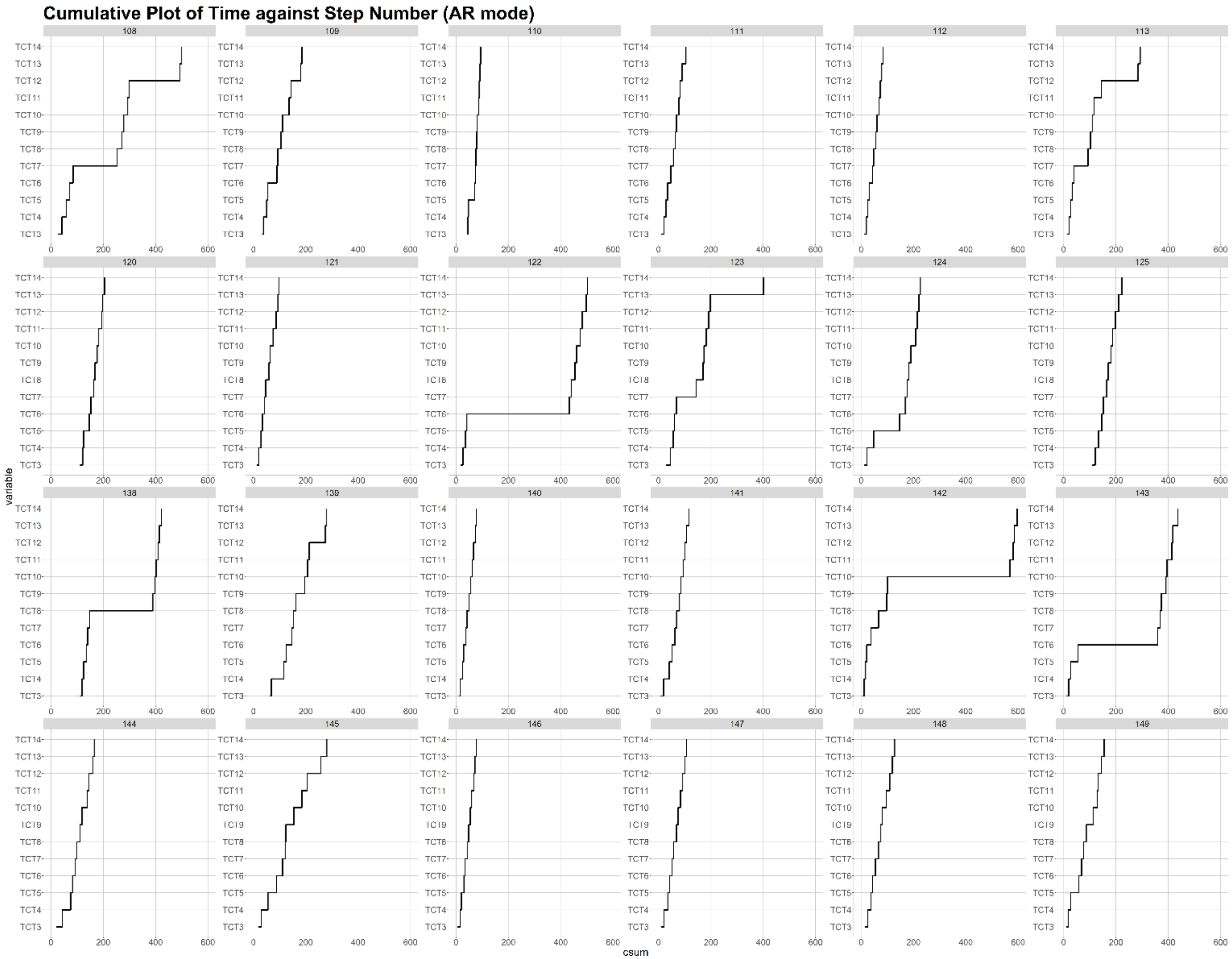


Chart 6.21 - Time series of step number against cumulative time taken to complete task using wearable AR instructions

As before, the data presented in Chart 6.17, Chart 6.18, and Chart 6.19 are based on raw values for each performance measure. From here onwards (Sections 6.4.2.1, 6.4.2.2), delta values will be used instead as described in Section 6.3 and in Table 6.15.

Table 6.15 – Interpreting the delta values in experimental results – AR versus paper instructions

	Positive value	Zero	Negative value
ΔTLX	This option required more cognitive effort for AR than paper on average	No difference	This option required less cognitive effort for AR than paper on average
ΔER	This option resulted in more errors for AR than paper on average	No difference	This option resulted in fewer errors for AR than paper on average
ΔTCT	This option took longer to complete the task for AR than paper on average	No difference	This option took a shorter time to completed for AR than paper on average
ΔSUS	This option was rated as more usable on average for AR than paper instructions	No difference	This option was rated as less usable on average for AR than paper instructions

6.4.2.1 Display Mode

Presented in Table 6.16 is a summary of results for each performance measure, broken down by method of displaying AR content.

Table 6.16 - Mean and standard deviation of each performance measure by display mode

	ΔTLX		ΔER		ΔSUS	
	mean	s.d.	mean	s.d.	mean	s.d.
cad	8.85	18.7	0.25	0.661	21.6	24.4
text	10.5	16.1	0.125	1.36	21.9	14.3
video	-1.88	23.3	1	1.22	6.25	25.0

Though a simple comparison of means may indicate considerable differences in Task Load Index as a result of changing Display mode, when taking into considering the large variation within each condition, the situation becomes less clear.

As in Trial 1, the results were analysed using the MANOVA technique to look for areas of significant difference in multivariate data.

Table 6.17 shows that no statistically significant difference existed in cognitive effort (TLX score), accuracy (error rate) or usability (SUS) between the different display modes examined.

Table 6.17 - MANOVA test for significant differences between different conditions for each of the dependent variables

	TLX	ER	SUS
Display	0.451 Not significant	0.310 Not significant	0.328 Not significant

As stated in Section 6.4.2, Task Completion time was analysed separately from the other factors, using the Kruskal-Wallis non-parametric test. The output of the test is shown in Table 6.18.

Table 6.18 – Output of the Kruskal-Wallis test looking for differences in Task Time based on Display Mode

	Chi-Squared	df	p-value	Significance
Display Mode	0.155	2	0.925	Not significant

As the **p-value** is not less than 0.05, any differences in performance are not statistically significant. This suggests that Display Mode does not have any significant impact on assembly performance when following AR instructions on a wearable device.

Visual inspection of the boxplots for ΔTask Completion Time against Display Mode (Chart 6.22) confirm this, showing very small differences between the means of the three categories, while variance is relatively large.

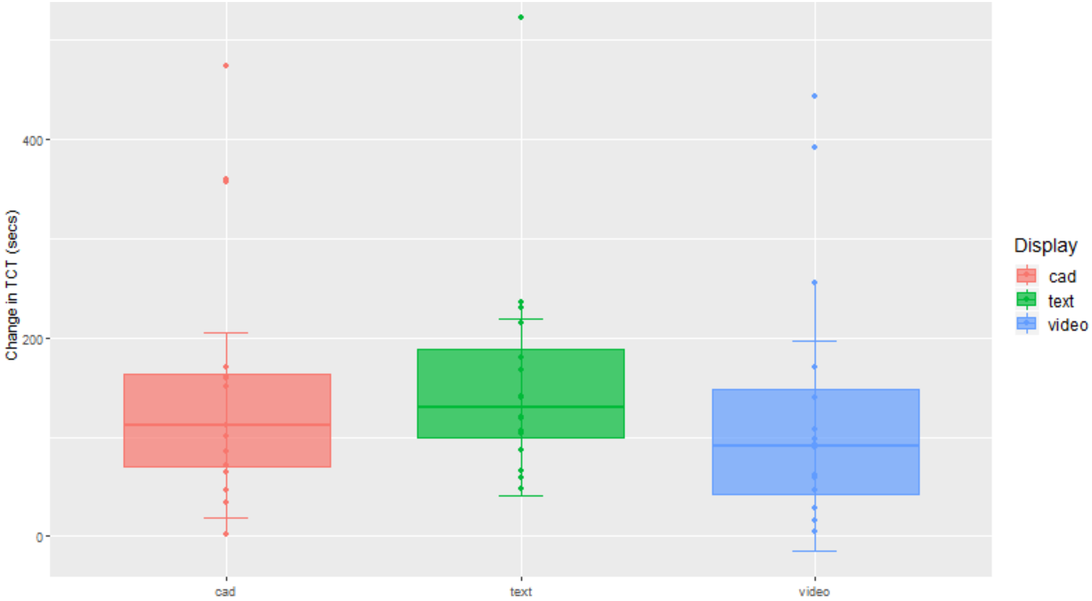


Chart 6.22 - Boxplot, dotplot and IQR of Display Mode against ΔTask Completion Time

6.4.2.2 Interaction Method

Table 6.19 contains some descriptive statistics showing how native (touchscreen) control of AR instruction flow affected the three dependent variables, compared to voice commands.

Table 6.19 - Mean and standard deviation of each performance measure by interaction method

	ΔTLX		ΔER		ΔSUS	
	mean	s.d.	mean	s.d.	mean	s.d.
native	10.7	21.1	0.667	0.624	19.8	25.7
voice	0.972	18.2	0.25	1.53	13.3	19.4

Table 6.20 contains results of the MANOVA analysis, which shows no significant differences for any of the three performance measures examined using this method.

Table 6.20 - MANOVA test for significant differences between different conditions for each of the dependent variables

	TLX	ER	SUS
Interaction	0.260 Not significant	0.413 Not significant	0.513 Not significant

There are small differences in the data for each performance measure, but these are not of great importance not being statistically significant at the 90% level or higher.

As in Section 4.5.1, data collected on Task Completion Time was analysed using the Kruskal-Wallis test, the results of which are presented in Table 6.21.

Table 6.21 – Output of the Kruskal-Wallis test looking for differences in Task Time based on Display Mode

Interaction Method	**Chi-Squared**	**df**	**p-value**	**Significance**
	0	1	1	Not significant

As the p-value is not less than 0.05, the differences between groups are not significant. This, along with the results in Table 6.20, demonstrates that Interaction Method also has no significant effect on assembly performance when using AR instructions on a wearable device.

Once again, visual inspection of the boxplot in Chart 6.23 (pg. 157) confirms the results of the statistical analysis. Comparing task times against method of interacting with content finds that means for both conditions are very similar, and there is significant overlap in the spread of results between the two conditions. There is little to suggest any differences in the mean results are due to anything other than random variation.

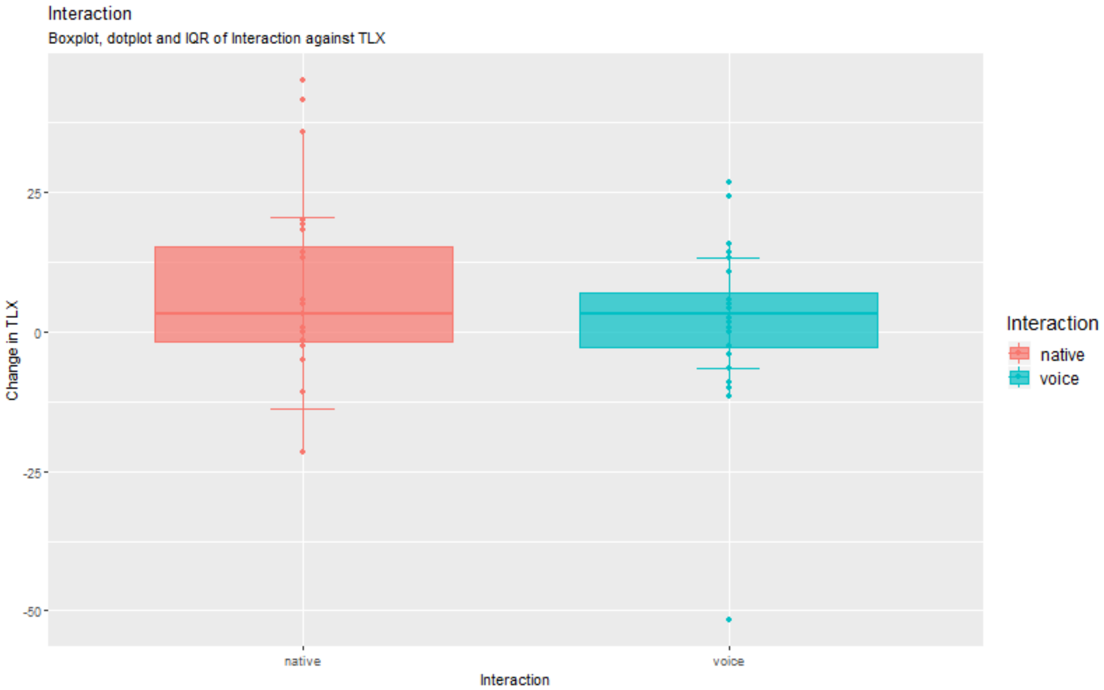


Chart 6.23 - Boxplot, dotplot and IQR of Interaction Method against ΔTask Completion Time

6.4.3 Discussion

Trial 2 found no significant differences in task time, error rate, task load index (NASA-TLX) or system usability when the selected UI factors (display mode and interaction method) were varied. This suggests that for AR instructions experienced on wearable devices, the impact of changing display mode or interaction method is negligible.

The data collected on task completion time did not meet the criteria for analysis using MANOVA techniques, so instead the Kruskal-Wallis non-parametric test was used to look for differences between groups. No statistically significant differences were found for either of the measured factors (display mode and interaction method), reinforcing the notion that neither of the UI factors considered had a large impact on assembly performance when AR instructions are displayed on a wearable device.

It should be noted that all these variables showed very large values of standard deviation in all cases. This suggests there was a large variation in performance between different individuals, which may be due to a lack of familiarity with technology, where those naturally pre-disposed to master new technologies quickly may have outperformed those who are more cautious to pick up new skills. This theory is bolstered further by the observations of Chart 6.22 (pg. 155), that the increased total task time was dominated largely by a few long pauses in the assembly, suggesting that a few participants were unsure or struggled to use the technology. It will be explored further in Section 6.6, in which Trial 4 investigates the effect of learning and familiarity on performance when following AR instructions.

6.5 Trial 3: Whole Dataset

In this section, both datasets from Sections 6.3 (Trial 1: Mobile AR) and Section 6.4 (Trial 2: Wearable AR) are used for analysis as a whole. This is permissible because both studies used the same basic methodology and processes, and collected data on the same performance metrics. By treating both studies as a single dataset, conclusions can be drawn as to which device type is most effective at conveying AR instructions for simple assembly tasks. Additionally, using the larger combined dataset makes it easier to identify potential interactions between the different factors investigated.

6.5.1 Assumptions

In order to draw robust conclusions from the data, it is necessary to test assumptions to see if the data is suitable for MANOVA techniques. Table 6.22 shows the output of statistical tests for skewness, kurtosis, and the Shapiro-Wilks test for normality.

Table 6.22 - Tests for Normality on each individual performance measure

Variable	Skewness	Kurtosis	Shapiro-Wilks Test
TCT	1.49 highly skewed	4.61 leptokurtic	9.06E-06 significant deviation
ER	0.329 approx. symmetric	5.21 leptokurtic	0.000164 significant deviation
TLX	-0.197 approx. symmetric	5.94 leptokurtic	0.00237 significant deviation
SUS	-0.337 approx. symmetric	3.91 leptokurtic	0.108 approx. normal

Task Time is skewed, leptokurtic, and strongly fails the Shapiro-Wilks test - alternate methods of analysis should be sought. Error rate and cognitive exertion (TLX score) both show deviation in the Shapiro-Wilks test, but this is known to be overly sensitive in small sample sizes. As the plotted curves in Chart 6.24 appear by visual inspection to be approximately normal, the analysis will proceed as planned but with some caution. Finally, Usability (SUS) meets assumptions of both skewness and normality, and though it tends to be leptokurtic, MANOVA is known to be relatively robust to violation of this assumption and so analysis will proceed as planned for this metric also.

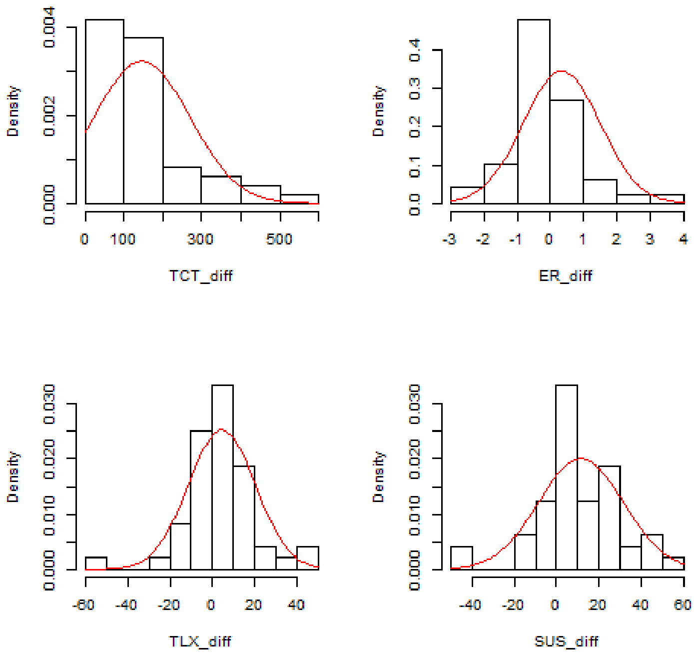


Chart 6.24 - Histograms of univariate distributions of dependent variables

The QQ-plots in Chart 6.25 (pg. 161) confirm that Task Time (TCT) deviates from the assumption of normality, as many points lie far outside the 95% confidence interval (grey shaded area) – therefore the Kruskal-Wallis nonparametric test will be used as an alternative to MANOVA, as in Section 6.4. All other variables show most points lie within or close to the confidence interval, so MANOVA will proceed as planned.

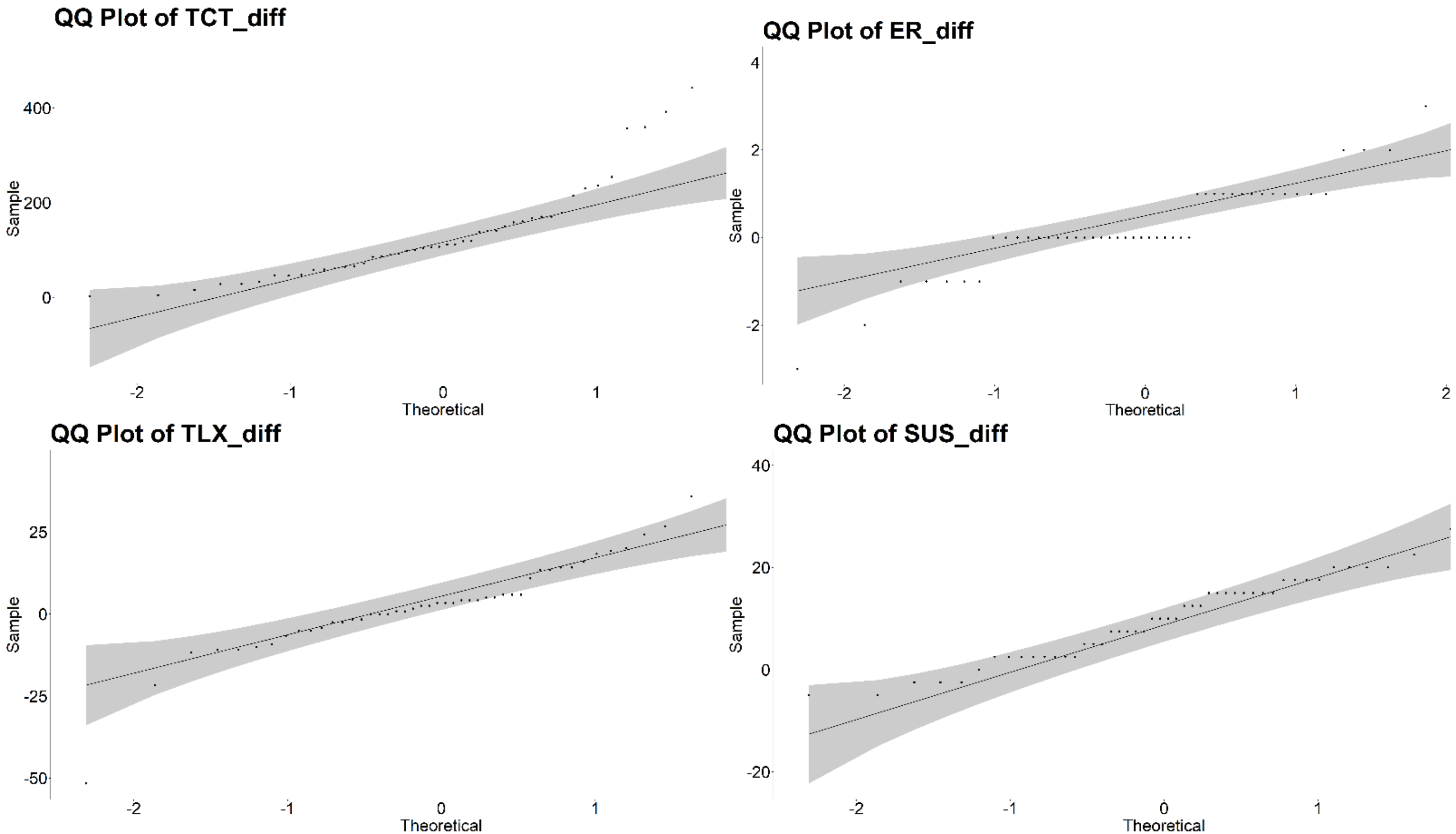


Chart 6.25 – Chi-Square Q-Q Plot to test for normality across all 4 dependent variables

6.5.2 Results of Trial 3

Table 6.23 shows a summary of results for the combined dataset, comparing user performance when using AR instructions overall against paper instructions.

Table 6.23 - Overall mean and standard deviation of each performance measure

	TLX		**ER**		**TCT**		**SUS**	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Paper	25.5	13.5	0.391	0.872	53.7	19.7	28.4	13.7
AR	29.3	14.6	0.696	1.2	224	144	40.3	15.5

As in the two previous studies, AR appears at first glance to be significantly slower than paper instructions overall, though the differences between the other factors are less clear-cut upon initial visual assessment (Chart 6.26).

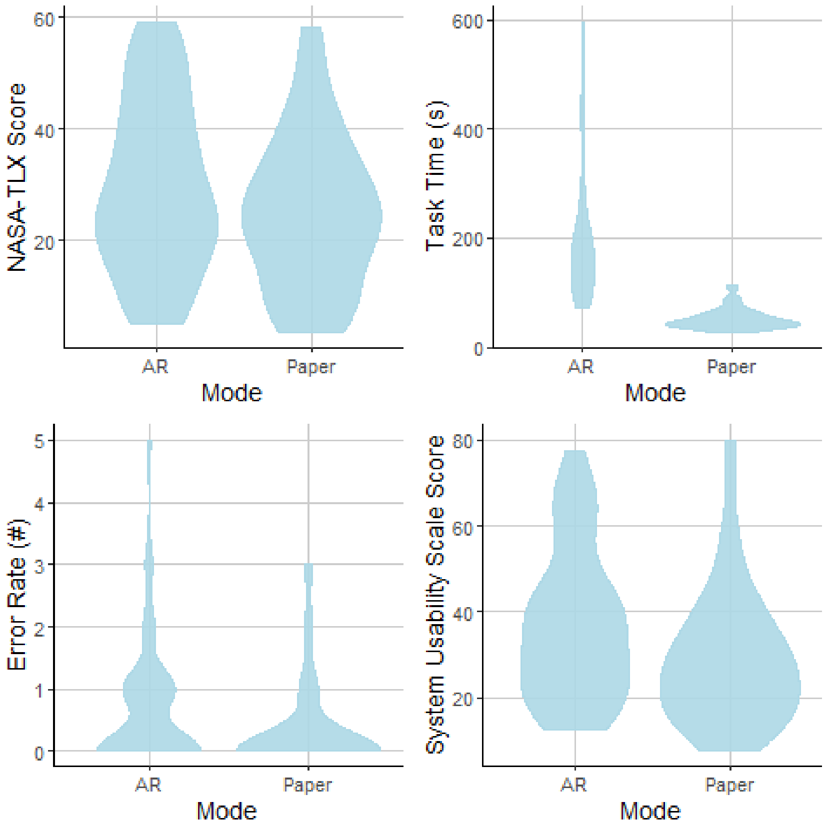


Chart 6.26 - Violin plot comparing all four dependent variables against instruction mode (Paper or AR)

6.5.2.1 Device Type

The novel part of this analysis, compared to that in 6.3 and 6.4, is the investigation of whether the type of AR device used influences user experience and performance. Table 6.24 shows a simple summary of the data for both mobile AR and Wearable (HMD) AR devices used.

Table 6.24 - Mean and standard deviation of each performance measure by device type

	ΔTLX		ΔER		ΔTCT		ΔSUS	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
hmd	5.83	20.8	0.458	1.22	189	157	16.6	23.5
mobile	3.16	8.54	0.208	1.10	104	51.7	6.35	14.2

Only Task Completion Time (TLX), Error Rate (ER) and System Usability Score (SUS) met the required assumptions for MANOVA analysis (as described in 6.5.1). The output of the MANOVA test is shown in Table 6.25.

Table 6.25 - MANOVA test for significant differences between different conditions for each of the dependent variables

	TLX	ER	SUS
Device	0.562 Not significant	0.459 Not significant	0.0750 Significant at the 90% level

Considering a threshold level of 90% significance (i.e.., a p value of less than 0.1), System Usability does appear to be significantly affected by Device Type used to display instructions. As there were only two levels of Device Type considered in this trial, pairwise comparisons such as Tukey's HSD were not required to determine where the differences existed. Visual inspection of the boxplots for system usability in Chart

6.27 does indeed imply that users rated the wearable AR option as being significantly more usable than its mobile equivalent system. This assertion is supported by comparison of means (from Table 6.24) which shows that Head Mounted Displays were rated as more than 60% higher on the System Usability Scale than Mobile AR.

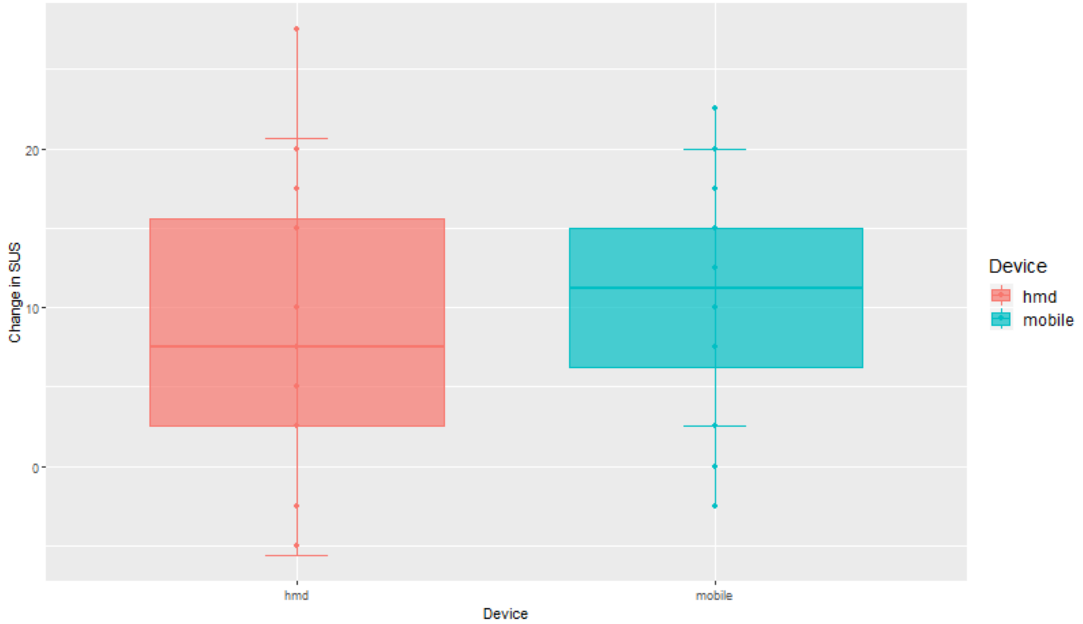


Chart 6.27 – Boxplot, dotplot and IQR of Device Type against ΔSystem Usability Score

As Task Completion Time did not meet the requirements for analysis by MANOVA, the Kruskal-Wallis test determined if device type causes significant differences in this factor. Table 6.26 shows the results of this test.

Table 6.26 – Output of the Kruskal-Wallis test looking for differences in Task Time based on Device Type

	Chi-Squared	df	p-value	Significance
Device Type	1.85	1	0.174	Not significant

The p-value is above 0.05 so no significant differences are identified, implying that Device Type does not have any notable impact on Task Completion Time in simple AR assembly tasks.

6.5.2.2 Display Mode

Table 6.27 contains summary statistics describing how the results varied depending how the AR content was displayed – 3D models, text-based annotations, or in-situ videos, regardless of device type.

Table 6.27 - Mean and standard deviation of each performance measure by display mode

	ΔTLX		ΔER		ΔTCT		ΔSUS	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
cad	5.68	15.7	0.0625	0.680	154	132	14.5	20.1
text	8.75	13.4	0.5	1.41	158	113	17.0	13.8
video	-0.938	17.3	0.438	1.26	127	130	2.81	22.8

As in Section 6.5.2.1, only TLX, ER and SUS met the requirements for analysis by MANOVA. Based on the MANOVA investigation, significant differences were discovered when using a threshold value of 90% confidence (i.e., a p value below 0.1).

Table 6.28 (pg. 165) shows that System Usability score was significantly different according to the method of content display, indicating that there is a 90% chance that these differences are due to the change in display mode, rather than simply random variation in the data.

Table 6.28 - MANOVA test for significant differences between different conditions for each of the dependent variables

	TLX	ER	SUS
Display	0.209 Not significant	0.521 Not significant	0.0953 Significant at the 90% level

Plotting the data using boxplots allows visual inspection of the data in Chart 6.28, which suggests in-situ videos scored slightly better on the usability scale than the other two options, with text-based annotations scoring slightly higher than 3D models (CAD).

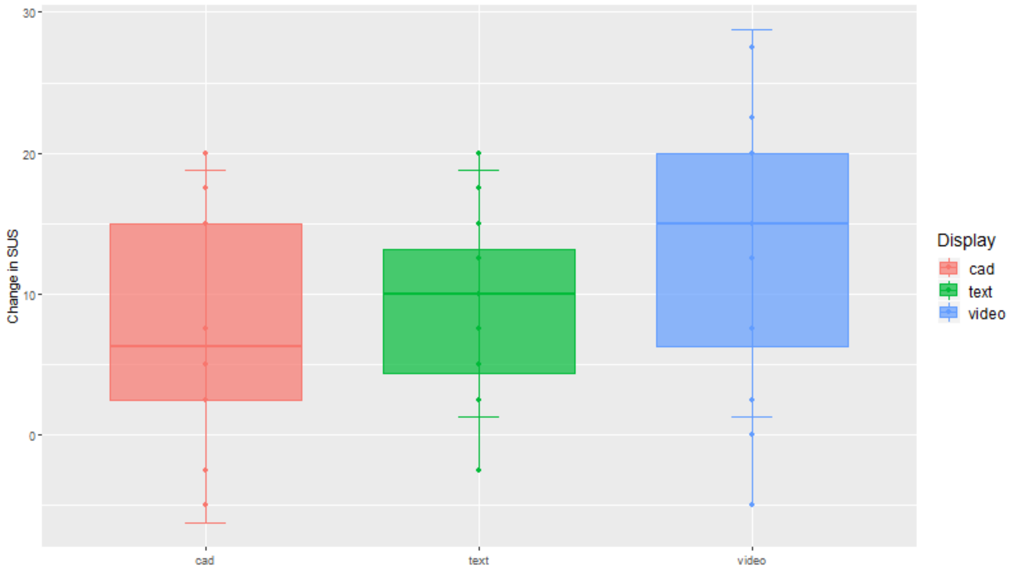


Chart 6.28 – Boxplot, dotplot and IQR of Display Mode against ΔSystem Usability Score

Next, the effect of display mode on Task Completion Time was considered, using a Kruskal-Wallis non-parametric test to search for significant differences in the data. According to the output of the test, the way in which content is displayed does not appear to cause any significant differences in task completion time based at the 90% confidence level (Table 6.29, pg. 166).

Table 6.29 – Output of the Kruskal-Wallis test looking for differences in Task Time based on Display Mode

	Chi-Squared	df	p-value	Significance
Display Mode	2.56	2	0.278	Not significant

6.5.2.3 Interaction method

Next, the method of interacting with AR instructions was investigated. Table 6.30 summarises the mean and standard deviation of each performance measure in the combined dataset, according to the interaction method – native (i.e. hand gestures) controls, or voice commands.

Table 6.30 - Mean and standard deviation of each performance measure by interaction method

	ΔTLX		ΔER		ΔTCT		ΔSUS	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
native	7.08	16.4	0.583	1.06	142	128	13.8	20.8
voice	1.91	15.0	0.0833	1.21	151	122	9.17	19.1

The effect of Interaction Method on TLX, ER and SUS can be explored through a MANOVA test. The results of this (Table 6.31) show no significant differences between methods of interacting with AR at the 90% confidence level (i.e., a p value of 0.1).

Table 6.31 - MANOVA test for significant differences between different conditions for each of the dependent variables

	TLX	ER	SUS
Interaction	0.260 Not significant	0.135 Not significant	0.431 Not significant

A Kruskal-Wallis test was used to investigate if Task Time was significantly affected by Interaction Method. Table 6.32 (pg. 168) shows the outcome of the Kruskal-Wallis test; – no significant differences were detected between the conditions at the 90% level, suggesting Interaction Method has little impact on performance when task time is considered a key metric.

Table 6.32 – Output of the Kruskal-Wallis test looking for differences in Task Time based on Interaction Method

	Chi-Squared	df	p-value	Significance
Interaction Method	0.43537	1	0.5094	Not significant

6.5.3 Other Factors

In addition to the controlled variables, several other factors could play a part in user performance. In this section, the impact of 3 additional factors on performance are investigated, as outlined in Table 6.33.

Table 6.33 – Extraneous variables considered for further analysis

Order	
Description	Order in which tasks were performed i.e. paper instructions first, or AR instructions first
Implementation	Recorded at the time of experiment
Motivation	Alternated by experimental design to reduce order effects but investigated again here to verify that this was successful.
Age	
Description	Age of the participant
Implementation	Self-reported via pre-experiment questionnaire
Motivation	(Sonderegger et al., 2016) suggests younger adults are less efficient at completing tasks using technical devices and emphasises that age should be a key consideration in UX research.
Gender	
Description	Gender of the participant
Implementation	Self-reported via pre-experiment questionnaire
Motivation	(Hou and Wang, 2013) found gender differences in assembly performance were reduced when using AR instructions as opposed to 3D manuals. Additionally, (Dirin et al., 2019) report conflicting results regarding gender differences in technology adoption, and conclude that it warrants further investigation.

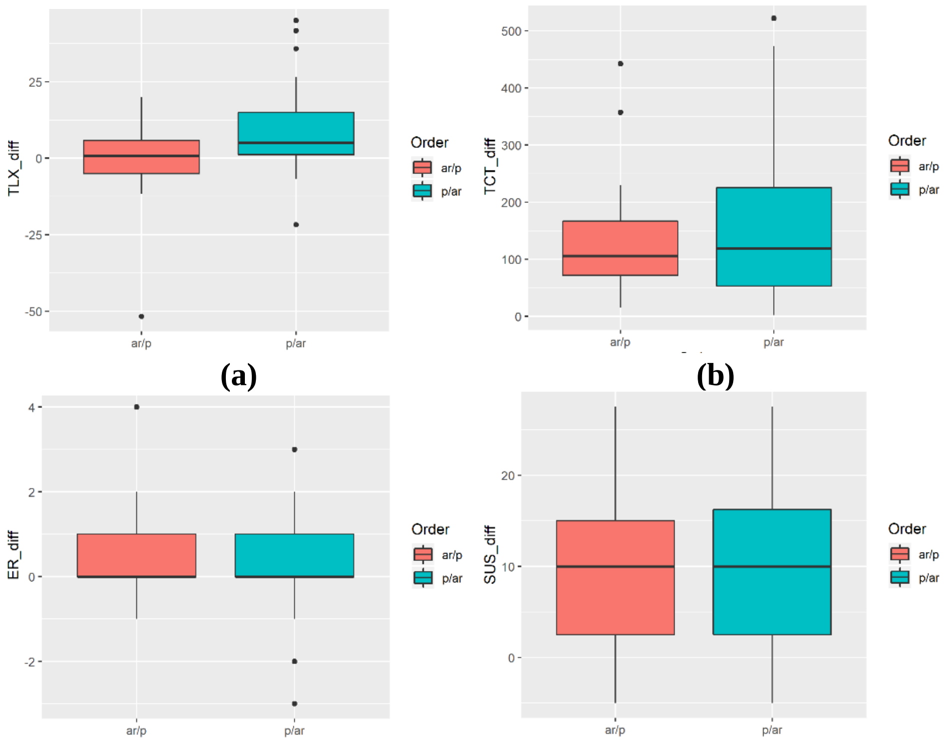
In Table 6.34 is a brief breakdown of participants by the 3 factors considered (age, gender, and order of participants).

Table 6.34 – Breakdown of participant demographics by age, gender, and order

n = 48	Order		Age		Gender	
	Paper then AR	**AR then paper**	**18-25**	**26-65**	**male**	**female**
#	12	12	23	25	39	9

6.5.3.1 Order

From simple visual inspection of the bar charts in Chart 6.29, there is no difference in any of the performance measures. This confirms that alternating the order of the tasks has cancelled out potential order effects that may have influenced the results in this chapter.



(c) (d)

Chart 6.29 – Boxplot of order against (a) ΔNASA-TLX, (b) ΔTask Time, (c) ΔError Rate, and (d) ΔSystem Usability

6.5.3.2 Age

In the initial data collection, age was split into three categories: 18-25 years old, 26-40 years old, and 41-65 years old. These categories broadly align with **Generation Z** (born after approx. 1995), **Millennials/Generation Y** (born approx. 1980-1994) and **Generation X** (Born before 1980) (McCrindle and Wolfinger, 2009). However, only two participants fell into the 41-65 category, therefore they were combined to create the two categories shown in Table 6.34, 18-25 years and 26-65 years (i.e., Gen Z and not Gen Z) to allow meaningful comparison of two roughly equal sized groups. This will be an interesting comparison as Generation Z are widely considered to be digital natives, meaning they have grown up since the advent of affordable computing and smart phones, whereas Millennials and Generation X have to varying extents adopted technology at later stages in their lives.

Chart 6.30 (pg. 171) shows boxplots for each of the dependent variables by age group. From visual inspection, the lower age group appears to have lower cognitive effort (TLX), slightly slower task completion, similar error rates, and slightly higher usability scores.

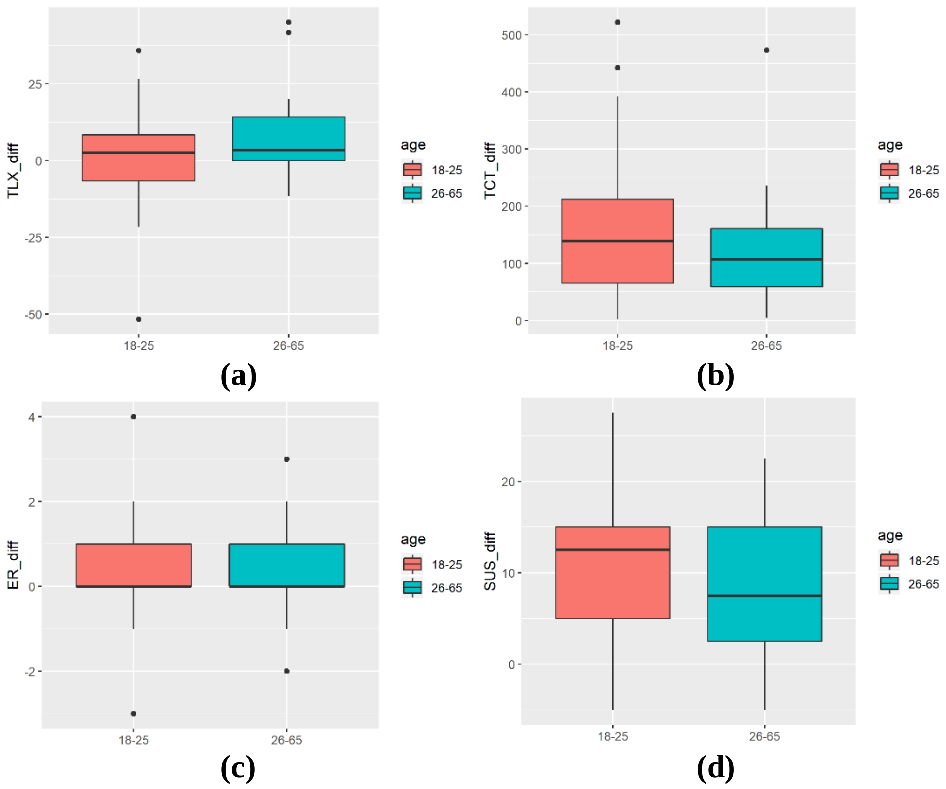


Chart 6.30 – Boxplot of age group against (a) ΔNASA-TLX, (b) ΔTask Time, (c) ΔError Rate, and (d) ΔSystem Usability

A student's t-test each of the variables explored if these differences are statistically meaningful (Table 6.35). All four p-values were above 0.05 so it appears there are no significant differences between the age groups at the 95% confidence level.

Table 6.35 – Student's t-test to determine significant differences by age group

		mean	t	df	p-value
TLX	**18-25**	1.30	-1.34	41.4	0.187
	26-65	7.43			
TCT	**18-25**	170	1.29	37.9	0.261
	26-65	124			
ER	**18-25**	0.304	-0.164	43.5	0.871
	26-65	0.360			
SUS	**18-25**	11.6	1.33	45.8	0.191
	26-65	8.50			

6.5.3.3 Gender

Due to the gender imbalance of the sample, meaningful statistical analysis of participant gender is not possible. Chart 6.31 suggests that there may be differences in performance based on gender. However, with such a small sample of female participants, further investigation is required.

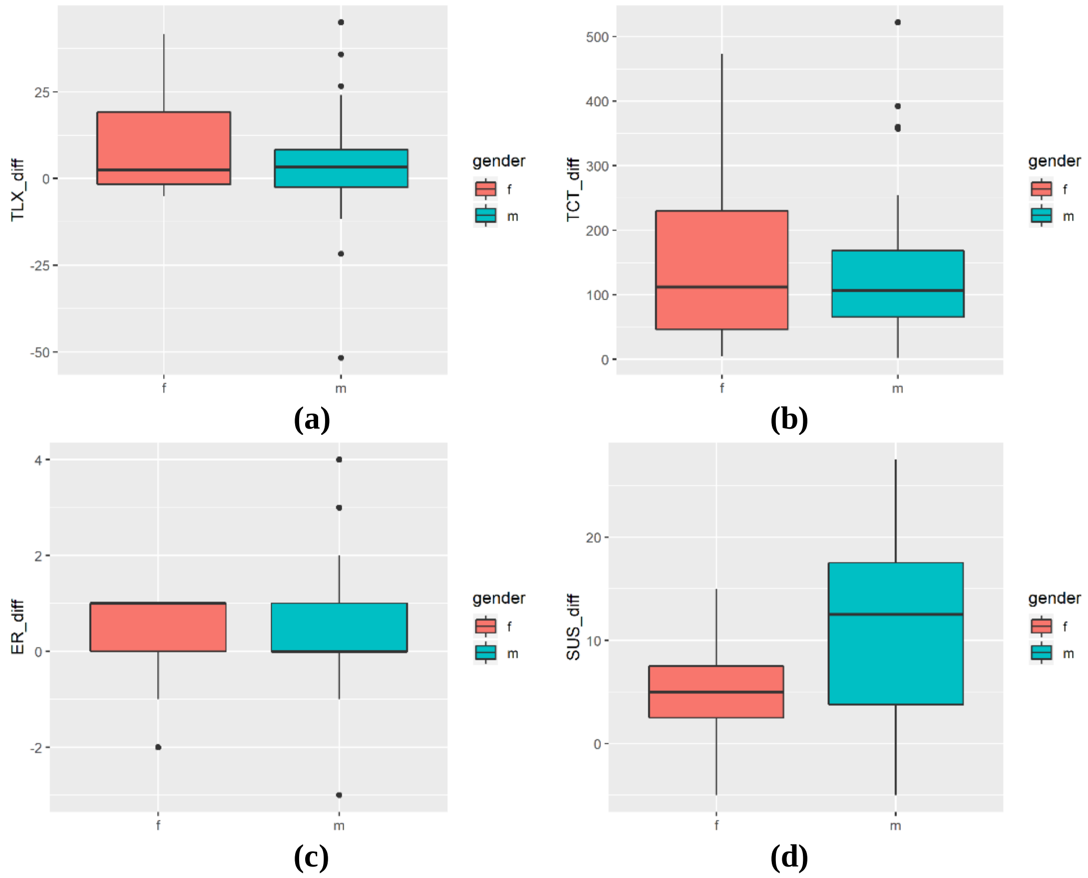


Chart 6.31 – Boxplot of gender against (a) ΔNASA-TLX, (b) ΔTask Time, (c) ΔError Rate, and (d) ΔSystem Usability

Therefore, gender disaggregated data is provided in Appendix D.4 with the intention that future studies considering the impact of gender on user experience in AR instructions may use it to form part of a meta-analysis.

6.5.4 Discussion

This section of the chapter (6.5) combined the datasets gathered in 6.3 and 6.4 to form one single dataset to allow comparison between Wearable and Mobile AR devices, as well as providing a larger dataset to explore Display Mode and Interaction Method with greater confidence in detecting small differences in the data. As in previous sections, tasks were completed faster when using paper instructions than any kind of AR overall. However, AR instructions scored slightly better on System Usability.

Each factor – Device Type (Section 6.5.2.1), Display Mode (Section 6.5.2.2), and Interaction Method (Section 0) – were compared according to the same four performance measures. Participants rated wearable devices as significantly more usable than mobile AR at a 90% confidence level. Further, text-based annotations were the most successful way of displaying AR instructional content, scoring higher on the usability scale than 3D models with 90% confidence. Therefore, this analysis suggests the most effective way to display content would be using text-based annotations on a head mounted display. There were no indications of significant differences between any of the Interaction methods investigated, backing up the suggestions in Sections 0 and 0 that this decision is best made based on other factors in the operating environment, such as noise levels or PPE that may impair access to the instructions.

Section 6.5.3 investigated three factors to determine if order blocking of extraneous variables was successful, and to explore any possible effects of user demographics on the variables measured during in Sections 6.3 - 6.5. The order of tasks (Section 6.5.3.1) alternated to eliminate order effects from having completed a similar task already.

Visual inspection of the boxplots for each category revealed the distributions were virtually identical, implying that the order blocking was successful. This confirms the validity of the studies carried out in Sections 6.3 - 6.5. Section 6.5.3.2 explored the effect of age on performance measures. Plotting the performance measures against age group of participants, revealed some variations in mean values depending on age group. However, analysis by the student's t-test revealed that none of these differences were large enough to be considered statistically significant. Therefore, one can conclude that UX design of AR industrial instructions do not need to be altered depending on the anticipated typical age of users. Similarly, boxplots breaking down performance by gender of the participant revealed differences in the means of all four factors considered (Section 6.5.3.3). However, only nine of the 48 participants sampled were female, which makes the sample very unbalanced and further analysis may be unreliable. Appendix D.4 contains full gender disaggregated data for future meta-analysis, but this work does not explore gender any further.

6.6 Summary

In order to achieve Research Objective 2, to discover the best way of presenting procedural instructions in AR, Chapter 6 sought to answer the following questions.

1. *Are head-worn AR or paper-based instructions more effective guidance system for participants performing a simple assembly task?*

Trial 1: Mobile AR found that paper-based instructions allow users to complete assembly tasks faster than AR instructions. However, AR is more usable overall, and specifically head worn displays are preferred to mobile devices (Section 6.3). Although this may be in part due to a lack of familiarity with new technology – Chapter 7 investigates this possibility further.

2. *Is voice control or gesture control a more effective mode of interaction with AR guidance systems when performing a simple assembly task?*

The way in which users interact with AR content did not have a significant impact any of the performance measures considered (Sections 6.3.2.2, 6.4.2.2, 0), therefore this decision should be based on user preference or workplace conditions.

3. *Are AR instructions easier to understand when presented as text, 3D models, or animations when performing a simple assembly task?*

When using mobile AR, in-situ videos allow users to complete tasks more quickly and with fewer errors (Section 6.3.2.1). The decision is less clear-cut when using wearable

AR; however, the data would suggest that text-based annotations are the preferred option due to their better usability rating (Section 6.4.2.1).

In addition to the main research questions, some additional demographic factors were also considered in Section 6.5.3 – while no significant differences were found based on age, there was insufficient gender balance in the data to draw any conclusions about how gender affects performance or UI preference, and this is suggested as an avenue for future work.

7 The Effect of Novelty and Learning in AR Instructions

7.1 Introduction

In Chapter 6, participants using paper instructions consistently achieved better task times and error rates than when using AR. One explanation for this is that the Lego task used in Chapter 6 was very simple and so was not well suited to AR guidance. Indeed, Syberfeldt et al. (2015) suggest that AR is better suited to tasks that are more complex. However, another possibility is that lack of familiarity with the technology may be a barrier to good performance when using AR instruction guidance, as suggested by Blattgerste et al. (2017) in their comparison of different instruction modes.

This chapter therefore explores how familiarity with AR instructional systems affects user performance, fulfilling **Research Objective 3 - To investigate the effect of learning and novelty on performance when following AR instructions**.

There is little research into how technology familiarity impacts performance for AR, but several existing studies confirm that familiarity with PCs and tablets improve performance at PC- or tablet-based tasks respectively (Tomasi et al. (2018), Chen et al. (2014), Jeong and Yoon (2017), Goldberg and Pedulla (2002)). Therefore, there is certainly reason to explore whether a similar relationship may exist in AR technology.

Conversely, it may be that the excitement of using a novel learning tool was the reason behind improved usability scores for the AR conditions. Consequently, an experiment was devised to discover how performance metrics change over time as familiarity with AR instructions grows.

7.2 Methods

As discussed in Section 4.6, Trial 4 was designed in such a way that it could be carried out remotely, meaning any equipment used had to be either readily available in an ordinary home, or low cost and light weight enough to be sent to participants through the post. The latter option was chosen.

Because of this, only UK-based participants were eligible. They were volunteers from a mixture of backgrounds, contacted through professional and social networks, or identified as those who had previously taken part in the experiments described in Chapter 6. As well as items posted to their homes, participants also received an email containing instructions on how to access the instructions and a video demonstration to show how the system works (Appendix E.2). After that, the only support or guidance available to participants was via email, or information contained in the AR app. Participants were asked to complete a task once a day for at least five consecutive days. All who took part in the study were kept anonymous, and were referred to throughout the study by a 3-digit number starting with a 4 (i.e., 4XX), to signify that they were a part of Trial 4.

To test the effect of novelty and experience on performance, a task would need to be repeated by users multiple times over a period. If the task were the same each time, it would be impossible to tell if users were truly improving their ability to follow the instructions, or if they were just remembering the task from previous attempts. Therefore, the task required small variations for each repetition, but an overall similar difficulty level. Similar to the experiments in Chapter 6, Lego assemblies were used, partly due to the low experimental cost.

Lego was also an ideal option because it is small, relatively low cost, and safe to post. To make the task from Chapter 6 more suitable for postage, a simplified version of the assembly task was devised, stacking Lego bricks on a small baseboard in a slightly different pattern each day. The pattern was two layers of bricks in height, to take advantage of AR's 3D capabilities and used only 2x2 Lego bricks to minimise the number and size of bricks required. The order of the patterns was randomised between participants, as in Figure 7.1 to prevent any inherent differences in the task presenting themselves as a learning effect.

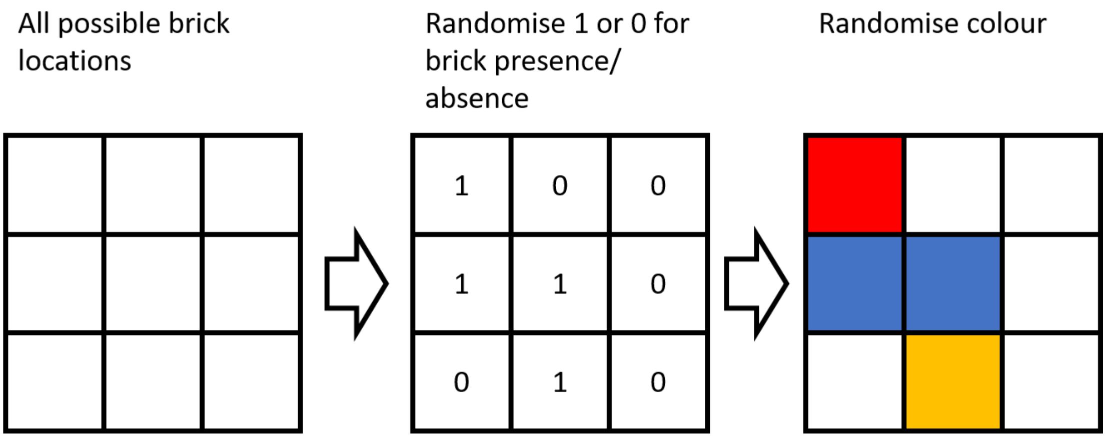
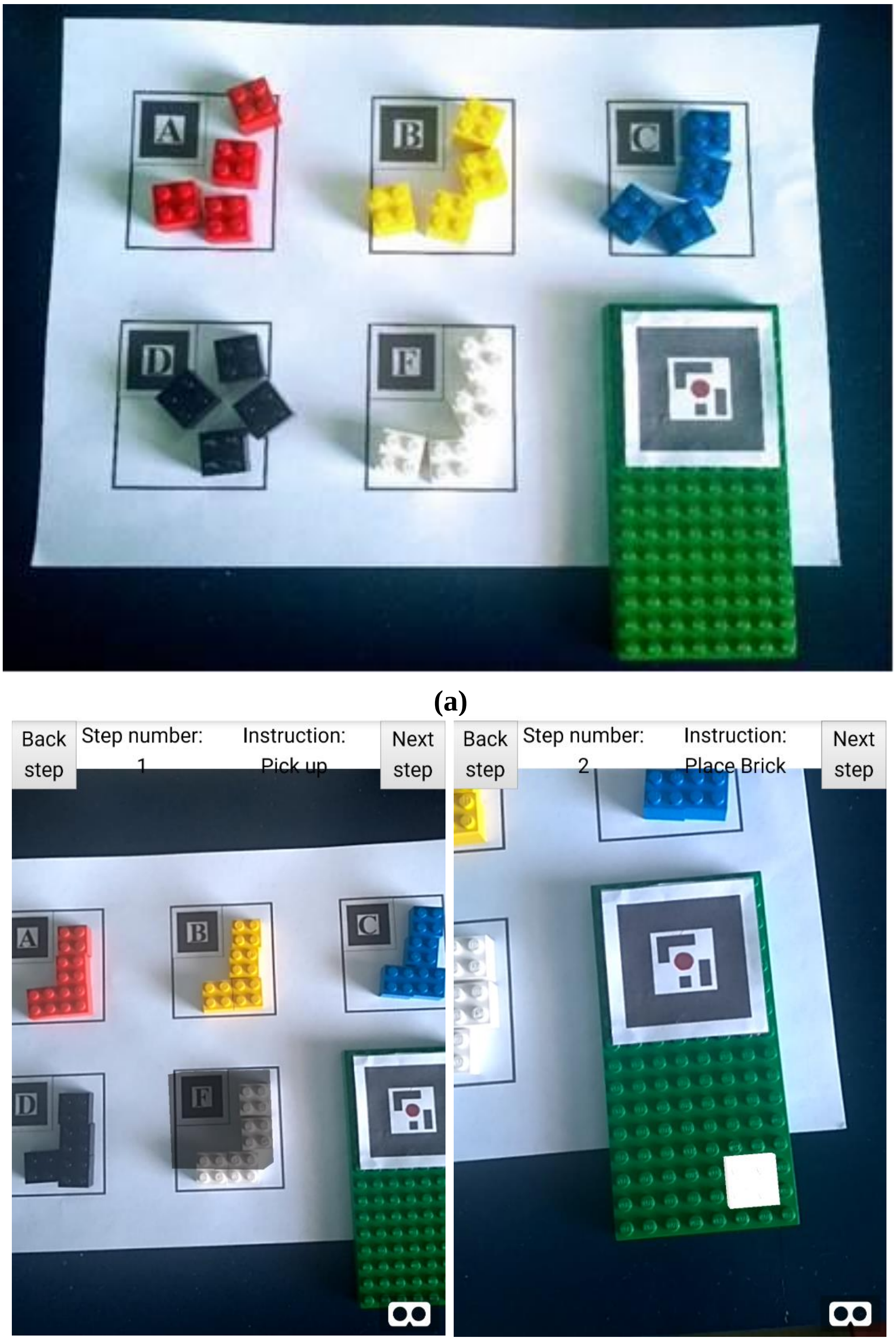


Figure 7.1 – Explanation of how brick colour/location was randomised in the instruction application

The base code for the learning app was recycled from that used in Chapter 6, from the 3D models content display and touchscreen (native) interaction mode. However, as shown in Figure 7.2 (pg. 181), the storage bins were replaced with a 2D printed grid for ease of delivery, and the 3D models were updated accordingly to match the new task.



(a)

(b) (c)

Figure 7.2 – (a) layout of the kit posted to participants, (b) screenshot of the AR instructions for a ‘pick’ step, and (c) for a ‘place’ step

As in Chapter 6, overall time was a key performance metric, so timestamps were generated and recorded when participants progressed through the instructions. The basic task took a minimum of 20 steps to complete, so any extra steps represented the number of user errors. This is not a wholly reliable metric, as without observation it is impossible to tell where exactly errors were made, if any were left uncorrected, or if errors were corrected without going back to consult a previous instruction. It does not directly tell the number of errors made, but if used consistently can form a proxy for error rate to compare performance between conditions. In the results table (Appendix E.3), the Errors column consists of the number of steps in each record minus the minimum number of steps to complete the task, 20.

The factors investigated in this chapter are summarised in Table 7.1, along with their abbreviated names:

Table 7.1 – Description and shorthand for dependent variables in this chapter

Task Completion Time	Time in seconds from start of task to completion	**TCT**
Error Rate	Number of errors (whether corrected or uncorrected) made during the task	**ER**

7.3 Results of Trial 4

The study required participants to complete the task at least five times, but several went beyond, completing the task up to 19 times. Forty users completed at least one assembly, dropping to 26 by the fifth repetition, and falling to just one for 12-19 task repetitions.

In Figure 7.3, the total time taken to complete each assembly was plotted against the number of times the participant had carried out a task. There is a clear decrease in total time to complete the task as users gained more experience with AR instructions.

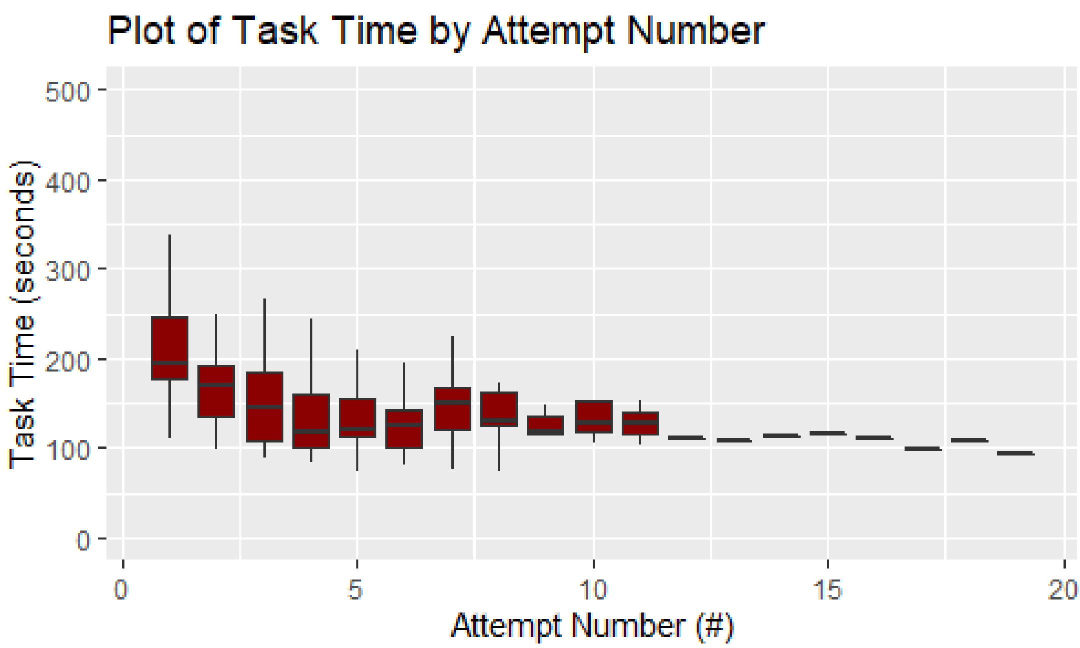


Figure 7.3 – Boxplot of time taken to complete the Lego task against number of previous attempts, outliers not shown

Figure 7.4 however does not demonstrate a clear trend in the approximate error rate as repetitions increase.

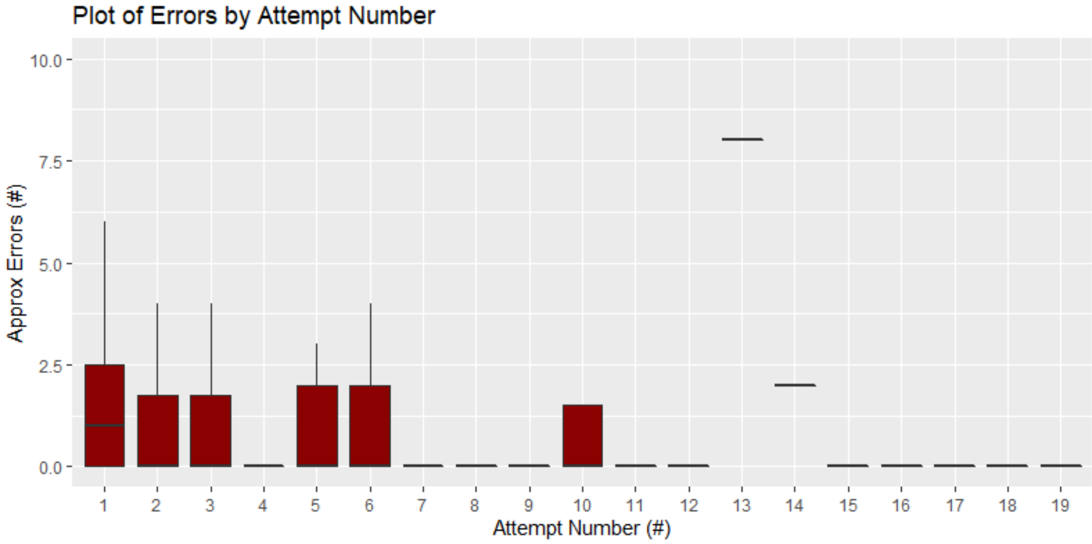


Figure 7.4 – Boxplot of approximate errors made against number of previous attempts; outliers not shown

A quantitative evaluation of performance was performed for both metrics - total task time and error rate - to determine if any significant differences were found when users had greater familiarity with the technology.

The two conditions used to compare performance were first attempt at the task, and fifth attempt of the task as this was the original number of repetitions required for the experiment. A two-sample t-test was performed, using the *t.test()* function from the '*stats*' package in R (The R Foundation, 2021). The results of this can be found in Table 7.2 (pg. 184).

Table 7.2 – Results of unpaired two-sample t-test between 1st and 5th attempts

	Average value		t	df	p-value	Significance
	1st	5th				
Total Task Time (secs)	282	135	2.99	64	0.00397	Significant at the 99% level
Errors (approx.)	4.74	2.54	0.971	64	0.335	Not significant

For task time, the p-value is below 0.01, meaning there is a 99% chance that there are true significant differences between the two groups. Examining the bar chart in Figure 7.3 (pg. 183) shows the direction of that difference, i.e., that attempt number 5 was significantly faster than the first-time users of AR instructions.

7.4 Summary

The study presented in this chapter set out to answer Research Objective 3: to investigate the effect of learning and novelty on performance when following AR instructions. The experiments presented here show that a lack of experience with AR may well have contributed to the performance differences seen in Chapter 6 between paper and AR instructions. With practice, it appears users become faster and more proficient at following AR assembly guidance. This confirms that the relationship between practice and performance in tablet- and computer-based tasks found in the literature (Section 7.1) seems to hold true for AR technologies also.

However, there is little evidence to suggest that this learning effect extends to a reduction in errors.

As a result, it is recommended that users with little or no experience with AR should be allowed a period of familiarisation, where they can practise and become comfortable using AR systems on a low-risk task, before moving onto real industrial tasks. In the context of the offshore wind industry, this may translate to reskilling existing employees to use AR technologies, in which case a mock assembly task similar to the Lego assembly presented here may be sufficient to introduce the new technology to users.

An average of 53% reduction in task time was noted after just five attempts, so it should not be prohibitively time consuming to include this as a step in AR implementation. The other option for implementing this advice is to embed AR skills in the incoming workforce by using devices from day one in the training of new employees such that they are familiarised with AR at the same time as learning the basic skills in their technician training. The concept of incorporating AR in technician training is explored further in Chapter 8.

The remote nature of this study introduces some uncertainty in the results, as per Section 4.6, due to a lack of direct observation of user behaviour. This particularly affects error data, so in future it would be ideal to repeat this study under more controlled conditions to see if any significant conclusions exist when error rate is observed more accurately.

8 Enhancing Vocational Training in the Post-COVID Era through Mobile Mixed Reality

8.1 Introduction

This chapter presents a study (Trial 5) to address **Research Objective 4: To explore novel methods of incorporating MR technologies into engineering training and education**.

Mixed Reality (MR) is proposed as a method of teaching practical tasks without the need for physical access to assets. COVID-19 and the resulting restrictions have had a massive impact on engineering education, particularly vocational and practical aspects of training. Employers reported an average of 17% of their apprentices having off-site learning suspended, including no access to online learning during April 2020, while many more were furloughed or made redundant (Doherty and Cullinane, 2020).

From this study and those outlined in Section 2.6, MR technologies have the capacity to supplement traditional education by simulating practical tasks and environments. However, there is a lack of robust data to support the idea that MR learning experiences are effective in achieving the desired learning outcomes. Given that learners may be accessing the content from their own homes, and on their own devices, it is important to keep technical requirements to a minimum to allow a broader range of users to access it. Therefore, Trial 5 examined the use of a low-cost, asynchronous remote learning system that uses AR to guide trainee electrical engineers to diagnose faults in a three-phase power supply.

A novel MR tool simulates and guides learners through a simple fault diagnosis of a three-phase power supply. The tool was web-based, in order to be widely accessible. A proof-of-concept case study is presented, in which MR is used to simulate an electrical panel and to guide users through a diagnostic process.

Please note: *this chapter is based on a previously published paper[4].*

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[4] *SMITH, E., MCRAE, K., SEMPLE, G., WELSH, H., EVANS, D. & BLACKWELL, P. 2021. Enhancing Vocational Training in the Post-COVID Era through Mobile Mixed Reality. Sustainability, 13, 6144. Adapted with permission under the Creative Commons Attribution License.*

8.2 Methods

According to Egger and Masood (2020) the most dominant device types in previous AR research were head-mounted displays, followed by hand-held displays (e.g., mobile phones, tablets, etc.). Trial 5 proposed MR to prevent loss of learning for students and home learners; therefore, the accessibility and low cost of the system were priorities. Figures show that 88% of the UK population owned a smartphone in 2019 (Deloitte, 2019), rising to 93% and 94%, respectively, in the 18–24 and 25–34 age groups. Therefore, a MR instructional application was designed using web-based technologies and lightweight visual tracking algorithms, so that it could be accessed even on a budget smartphone, so long as users had access to a camera and reasonably modern Web browser.

By utilising mobile-based AR, setup costs are minimal, as smartphones are so widely used and not prohibitively expensive for training institutions to supply if necessary. This was used alongside paper printouts, which could be provided as part of a textbook experience or as a standalone download.

The experiment, referred to subsequently as Trial 5 was advertised across media platforms and amongst existing contacts to recruit participants. After filling out a short sign-up sheet and background questionnaire (Appendix F.1), the 19 volunteers were split into two groups: those with backgrounds in electrical engineering (8 “expert” users) and those without (11 “non-expert” users). A summary of participants’ backgrounds and demographic data can be found in Table 8.1 (pg. 192).

Table 8.1 - Summary of participants' backgrounds, gathered via online survey

Task Experience	**Non-Expert**			**Expert**		
	11			8		
Age Group	**18–25 years**		**26–40 years**		**41–65 years**	
	6		8		5	
Gender	**Male**			**Female**		
	14			5		
Role	**Researcher /student**	**Engineer**	**Other academic**		**Other industry**	**No response**
	10	3	3		2	1
AR Ability	**1** (Never used AR)	**2**	**3**	**4**	**5** (Expert in AR)	**No response**
	2	5	8	3	0	1
Tech Ability	**1** (Not at all comfortable)	**2**	**3**	**4**	**5** (Extremely comfortable)	**No response**
	0	1	1	11	5	1
Digital Confidence	**1** (No confidence)	**2**	**3**	**4**	**5** (Very confident)	**No response**
	0	0	1	5	12	1

All participants were shown a short video to guide them through the operation of the application and were provided with a written explanation of how the app worked via email (Appendix F.2). Participants were kept anonymous and referred to by a 3-digit number beginning with a 5 (i.e., 5XX) to denote being part of Trial 5.

Both groups of participants were to follow the instructions in their respective apps to diagnose four different faults in the system. All participants were shown a short video to guide them through the operation of the application and were provided with a written explanation of how the app worked via email (Appendix F.2). Both groups of participants were to follow the instructions in their respective apps to diagnose four different faults in the system.

According to Egger and Masood, the most common measures in the industrial MR studies reviewed were time (39.5%), error rate (30.2%) and NASA-TLX (17.4%) (Egger and Masood, 2020). User acceptance was not the main success factor but still a big challenge (Masood and Egger, 2020), so freeform feedback was also considered important to capture the views of the users. The key performance measures considered were thus the time to complete each diagnosis, how accurate users were in correctly diagnosing faults and how many observations they required to make each diagnosis, which were all measured via timestamps recorded through app use.

After the end of the task, users were asked to answer a short survey to provide qualitative feedback and record the cognitive effort required based on the NASA-TLX scale, a measure of the mental, physical and temporal demand involved with tasks. Performance was then compared between the "experts" and AR-guided "non-experts" to gauge if the app was effective in teaching users how to take measurements and diagnose faults in three-phase power supplies.

The factors investigated in this chapter are summarised in Table 8.2, along with their abbreviated names:

Table 8.2 – Description and shorthand for dependent variables in this chapter

Task Completion Time	Time in seconds from start of task to completion	**TCT**
Error Rate	Number of errors (whether corrected or uncorrected) made during the task	**ER**
Cognitive Load	Mental effort required to complete the task, measured using the **NASA-TLX** scale (Hart and Staveland, 1988)	**TLX**
System Usability	Perceived ease of use of the system, measured using the System Usability Scale (Brooke, 1996)	**SUS**

Three-phase **AC (Alternating Current)** efficiently transmits high-voltage power from generation sites and distributes it over long distances across a network. Therefore, examining and diagnosing potential faults in a three-phase power supply is a common task across many industries, including the engineering services industry in which Booth Welsh, the industrial partner, operate. As relatively complex systems, there are opportunities for several different errors to occur, which must be identified precisely to repair the system. Therefore, this task was selected as a proof of concept for this technology.

Marker-based AR was used as a quick, robust method of locating and projecting AR content, and the hardware device chosen was the users' own mobile phones so that the study could be carried out remotely. The MR app was accessed via a webpage, which used the device's camera to provide a live stream of the real world.

Figure 8.1 (pg. 195) shows the physical print-out provided to participants. One marker (A-D, F-G, and Z) was placed next to each key point on the diagram, and participants used their mobile phones to scan the markers, triggering digital content to appear on their screens as an overlay to the real world. The user would see a video stream of the real world, overlaid with digital points highlighting where a voltage may be taken. They could then enter 'Take voltage mode' to use a simulated multimeter to take a reading by selecting the desired points to place the probes. Once a voltage measurement was taken, users would be directed to a screen showing an image of a digital multimeter and the readings from the two measured points. Sections 8.2.1 and 8.2.2 show more detailed descriptions of the app's functionality, along with screenshots of the app.

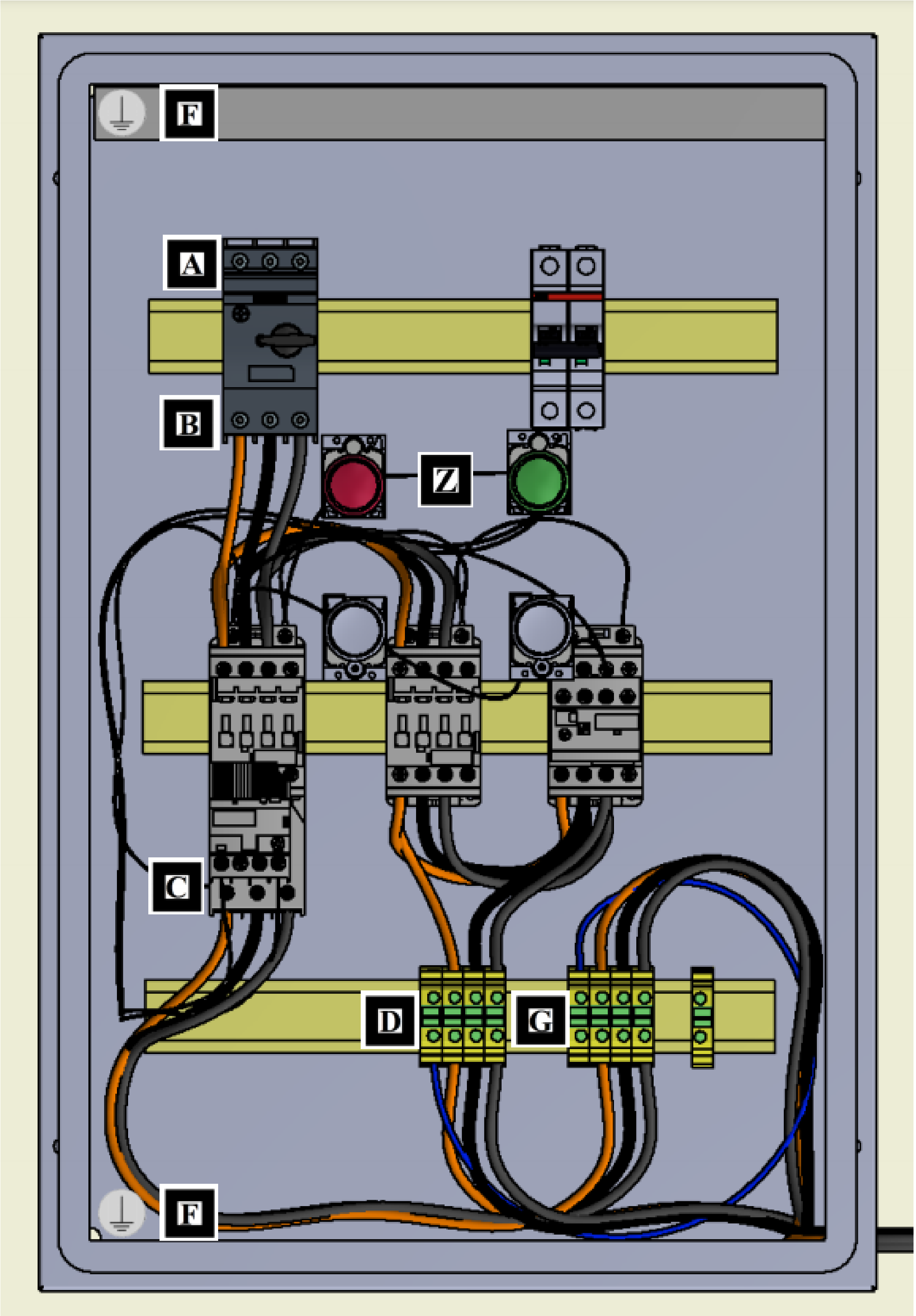


Figure 8.1 - Printout provided to users with markers (letters A-D, F-G and Z) to anchor AR content when viewed through the instructional application.

8.2.1 "Non-expert" version

For "non-expert" users, AR content directed the user exactly where to take readings (Figure 8.2, pg. 197). In some cases, it was also possible for users to make observations rather than measurements, such as whether the motor was running (Figure 8.2 c).

After each measurement or observation, the user was asked whether it met particular criteria (Figure 8.2 b) and, based on those answers, the app made suggestions as to what the fault was likely to be (Figure 8.2 d). The decision tree underlying this process is shown in Figure 8.3 (pg. 198). After receiving a suggestion, users could either submit, if they agreed with it, or, if they thought they had made an error in taking observations, they could restart the process.

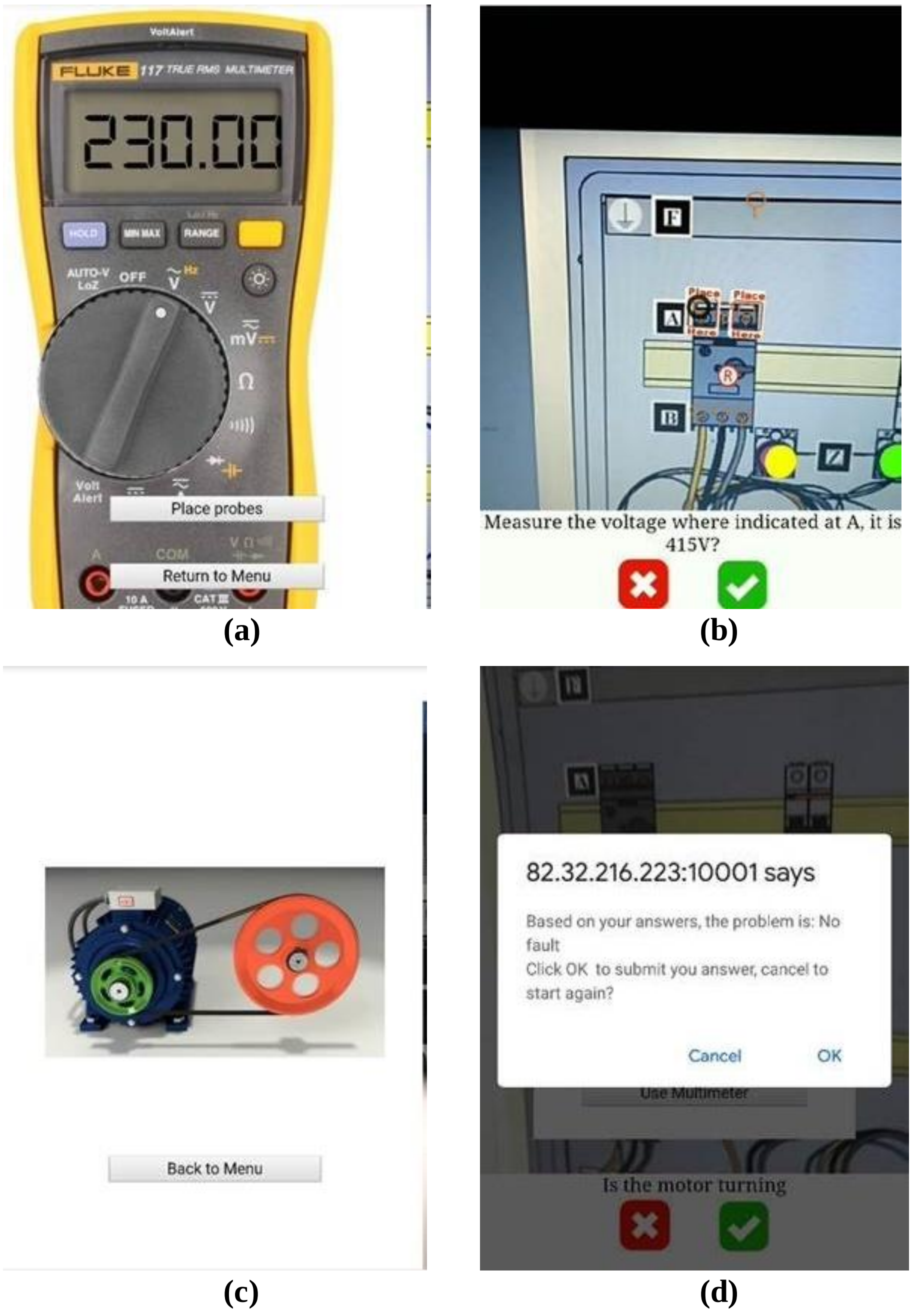


Figure 8.2 - Screenshots from the 'non-expert' version of the app, showing (a) the multimeter, (b) AR representation of the probes, (c) an animation of a motor, and (d) user selection of suspected faults

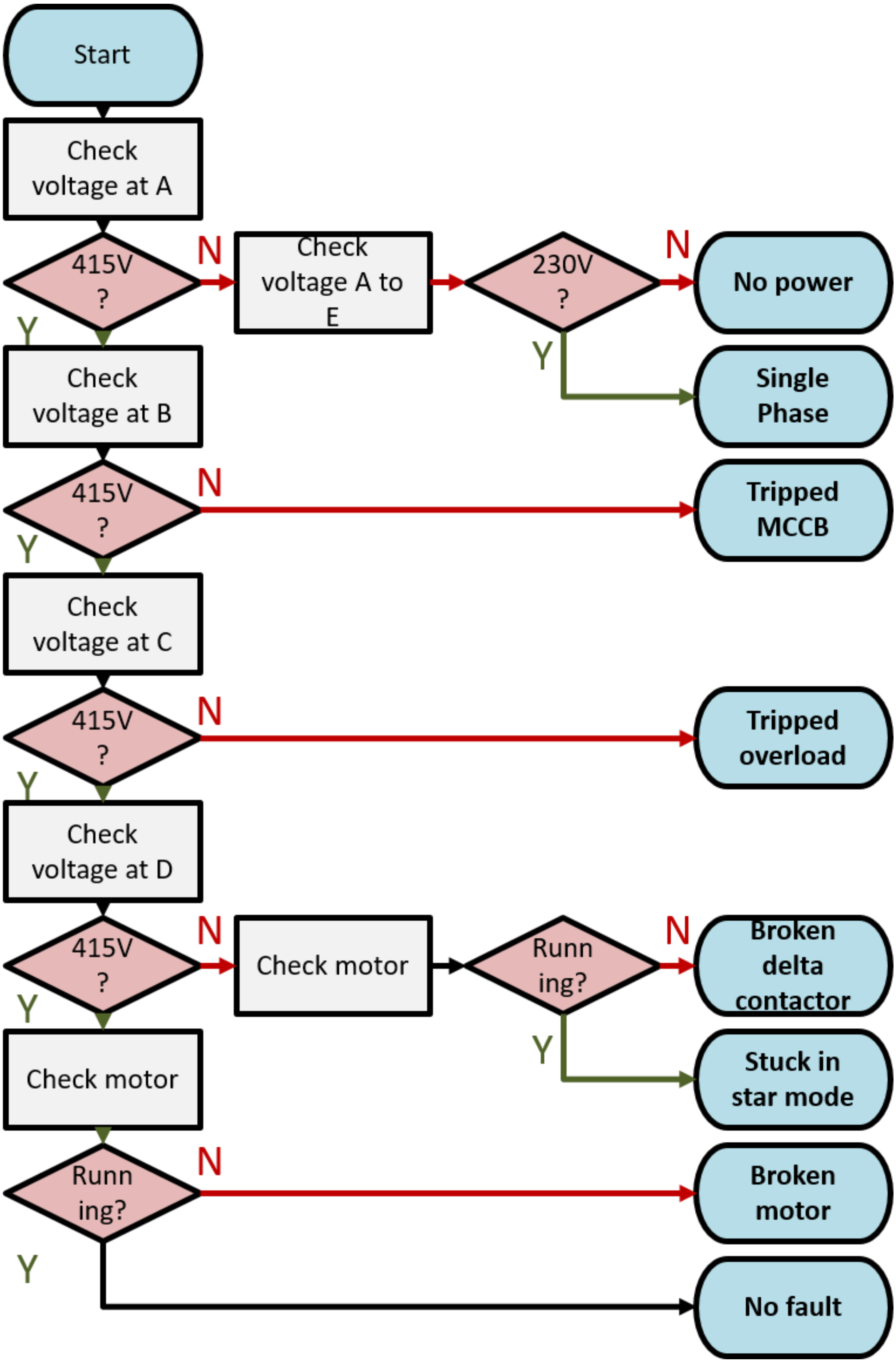


Figure 8.3 - Decision tree showing logic behind diagnostic guidance in the AR instruction app

8.2.2 “Expert” version

The “expert” user group consisted of those who self-identified as having a background in electrical engineering. In their version of the app, there was no additional guidance on where to take measurements and observations. Instead, users were free to place the virtual multimeter probes and take measurements and observations as desired (Figure 8.4, pg. 200). Once this was complete, they could submit a diagnosis from a list of eight possible answers, as shown in Figure 8.4 d.

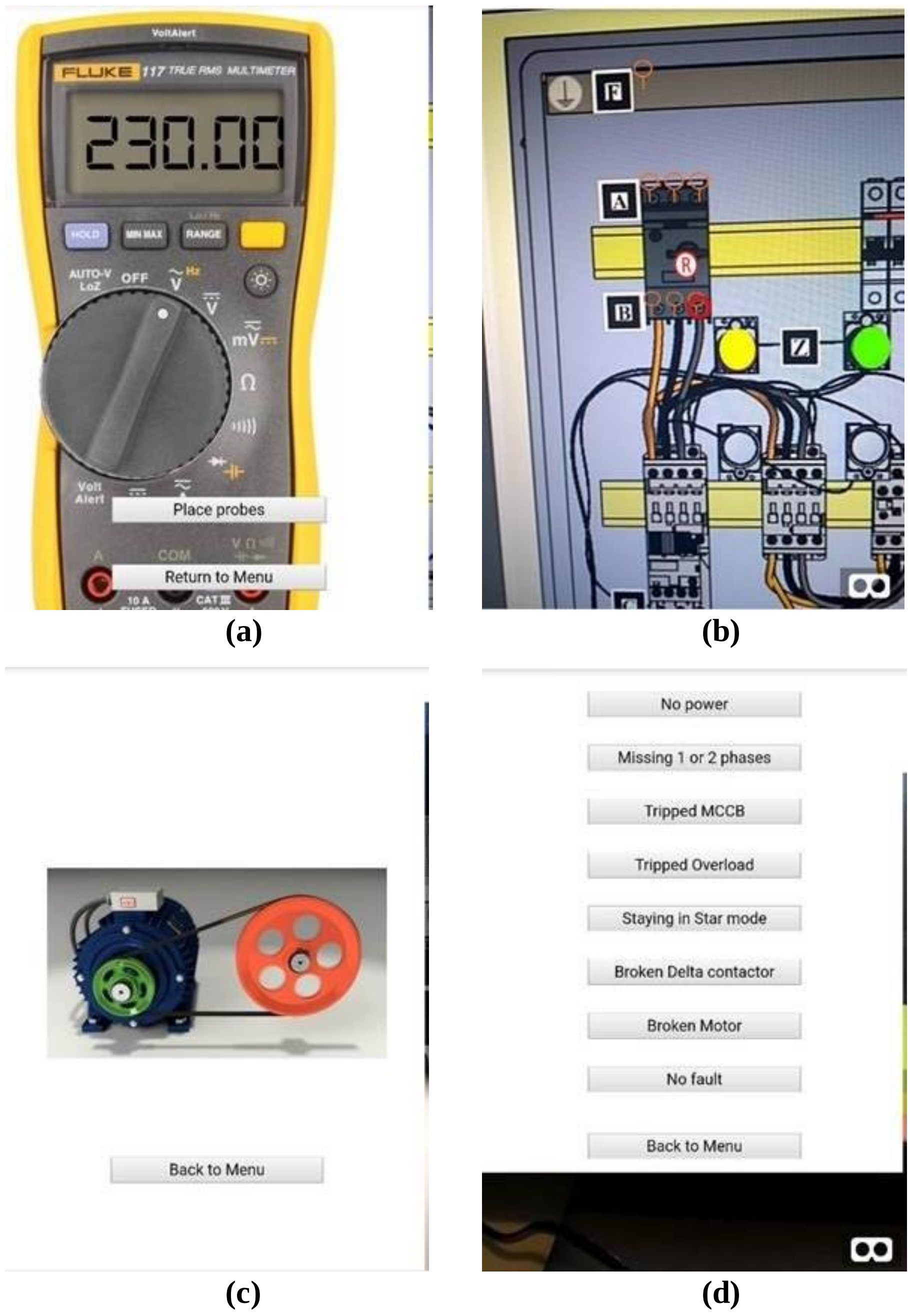


Figure 8.4 - Screenshots from the "expert" version of the app, showing (a) the multimeter, (b) the AR representation of the probes, (c) an animation of a motor and (d) user selection of suspected faults.

8.3 Results of Trial 5

On initial inspection of the mean scores, those in the guided "non-expert" condition outperformed those in the "expert" category across all metrics. On average, they were 65% faster in making diagnoses, 79% more likely to get them right and took 29% fewer observations before making a diagnosis (Table 8.3).

Table 8.3 - Summary of results for "expert" and "non-expert" groups

		Total Time (mm:ss)		**% Correct Diagnoses**		**Observations per diagnosis (#)**		**Time/observation (mm:ss)**	
	n	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***	***mean***	***s.d.***
Non-expert	11	07:31	03:23	58%	22%	18	10.9	00:21	00:33
Expert	8	21:36	18:21	30%	31%	32.1	22.5	00:30	02:36

These differences are examined further in Chart 8.1, Chart 8.2, and Chart 8.3 (pg. 202), which show the differences between each user group.

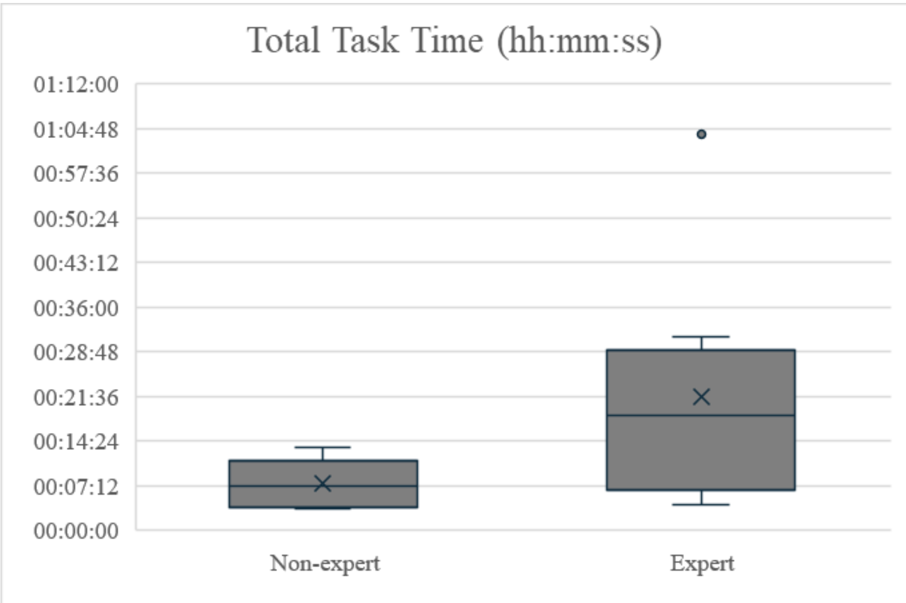


Chart 8.1 - Total time taken to complete the whole diagnostic task for expert and non-expert users

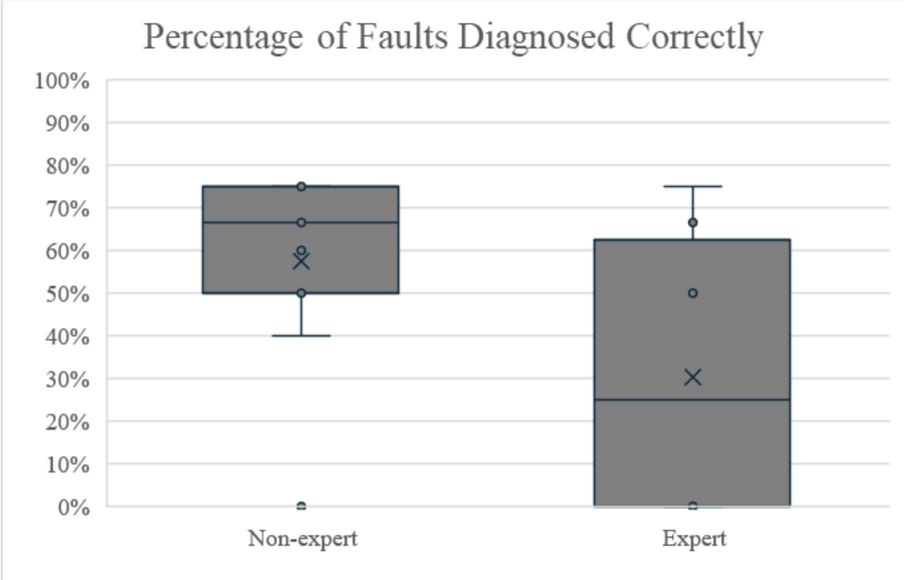


Chart 8.2 - Percentage of faults diagnosed correctly for expert and non-expert use

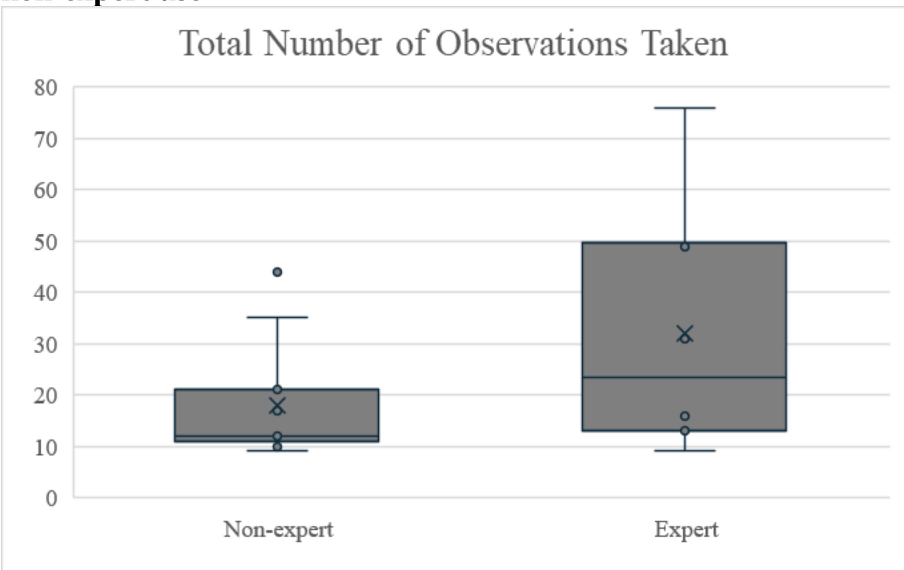


Chart 8.3 - Total number of observations taken by expert and non-expert users

A two-sample t-test was carried out on the timing data to infer whether the differences between the two groups could be considered statistically significant. A t-test requires the dependent variables to be approximately normally distributed in order to be valid, so Q–Q plots of task time, percentage of faults diagnosed correctly, total number of observations and raw TLX score were plotted to check for this assumption (Chart 8.4, pg. 203).

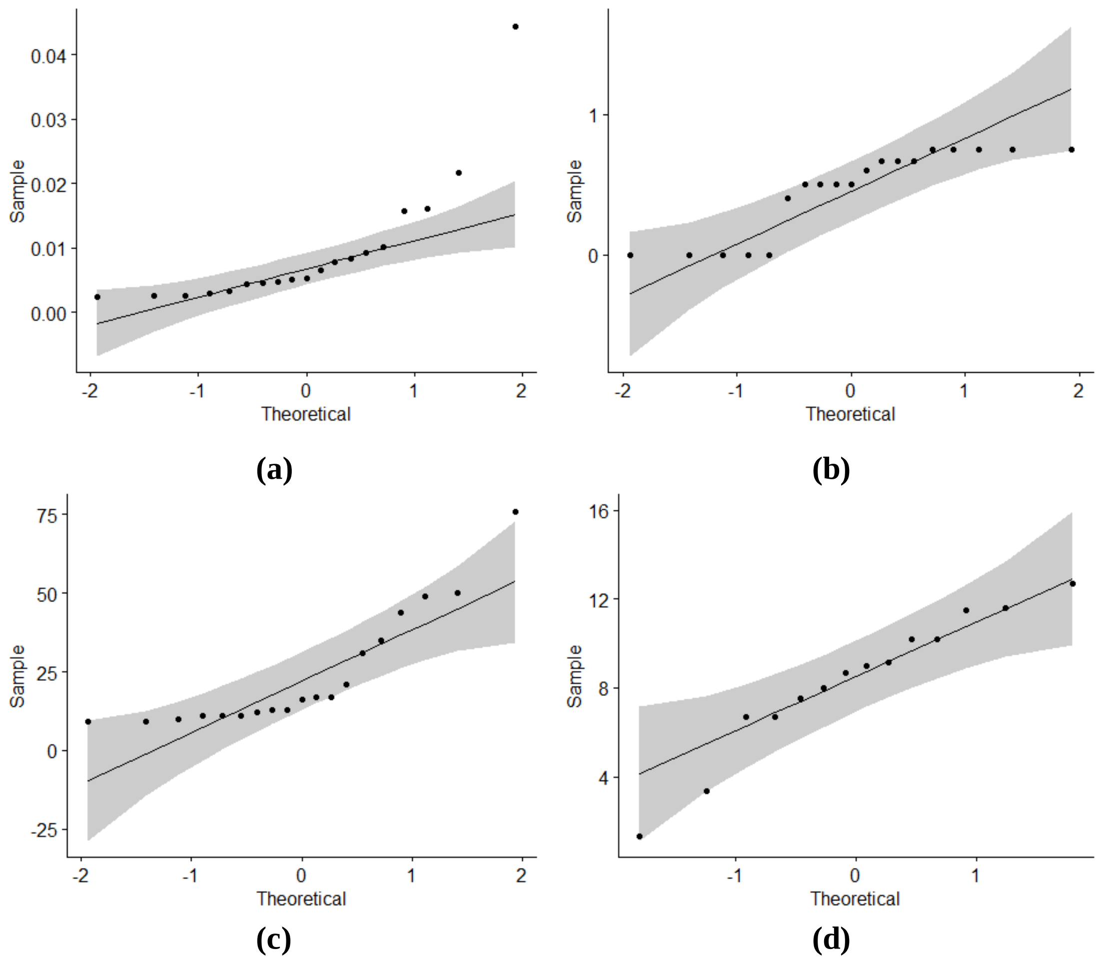


Chart 8.4 - Q-Q plots of (a) task time, (b) percentage of faults diagnosed correctly, (c) total number of observations and (d) raw TLX score

The grey shaded area in Chart 8.4 represents a 95% confidence interval. As most of the points lie within this region, and the t-test is relatively robust with regard to violations of the assumption of normality, analysis proceeded as planned. However, it is worth noting that distribution of task time data deviated somewhat from the normal distribution at the extremes of the distribution. A p-value of 0.08296 was found for task time, meaning that the result fell outside of the 95% confidence interval, but within the 90% interval. This implied that there was a less than 10% chance that the difference between the two conditions was due to random variation rather than a true difference in the population data.

A similar investigation of the percentage of faults correctly diagnosed found the difference between the two conditions to be below the standard 95% threshold for significance (p = 0.1104).

For the final metric measured during the experiment, a t-test investigated the differences between expert and non-expert performance in terms of the number of observations taken. A p-value of 0.1572 was found, so while the plots in Chart 8.2 appear to show a large difference between the two groups, statistical analysis suggests that the difference should not be considered statistically significant. Table 8.4 shows a comparison between the first and final diagnoses in the non-expert user group to see if performance improved with task duration.

Table 8.4 - Summary of task time and accuracy for first and final diagnoses

	Time (mm:ss)		**Percentage correct**	
	1st sub-task	**4th sub-task**	**1st sub-task**	**4th sub-task**
Average – expert	05:46	04:57	43%	20%
Average – non-expert	02:14	01:04	73%	60%
Overall average	03:37	02:22	61%	47%

Overall, users were on average 34% faster by the fourth sub-task compared to the first, but with a noticeable drop in accuracy, from 61% to just 47% of diagnoses being made correctly. This drop in accuracy was particularly acute in the expert user group. Non-expert users meanwhile experienced a relatively smaller drop from 73% accuracy to 60%.

Finally, optional qualitative feedback was collected from all users via a short online survey linked at the end of the four tasks (Appendix F.4). Just 17 of the participants responded to this section of the task. All respondents were asked questions aligned to the NASA-TLX scale and the results were processed to create a raw TLX score, rather than a weighted one, as 20 years of research has shown that weighting does not significantly affect outcome (Ratcliffe et al., 2021). Table 8.5 shows the results of this survey.

Table 8.5 - Summary of average unweighted (or "raw") TLX scores for each user group.

	Average NASA-TLX Score
Expert Users	9.75
Non-Expert Users	7.88

The "non-expert" users scored lower, suggesting that following the guided diagnostic process was generally less taxing than the experts using prior knowledge to complete the task. Chart 8.5 shows the unweighted (or "raw") TLX scores of participants resulting from the post-task questionnaire as a box and whisker plot in order to better show the spread of data. The non-expert user group had a slightly lower mean score; however, a two-sample t-test revealed a p-value of 0.381, suggesting the difference was not significant.

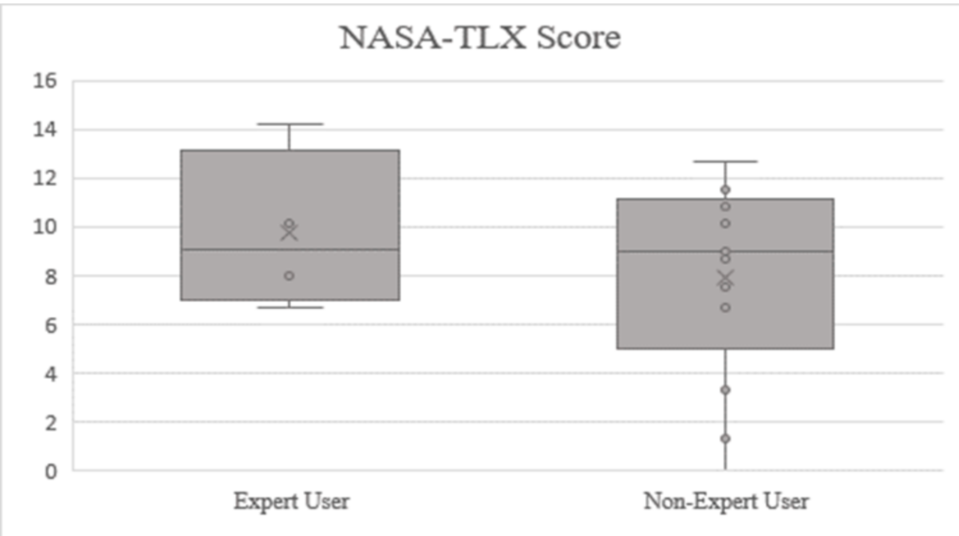


Chart 8.5 - Unweighted (or "raw") TLX scores as rated by expert and non-expert user groups.

"Expert" participants were also asked to rate the similarity of this simulated task to the real version. The results shown in Chart 8.6 suggest that it was a somewhat different experience.

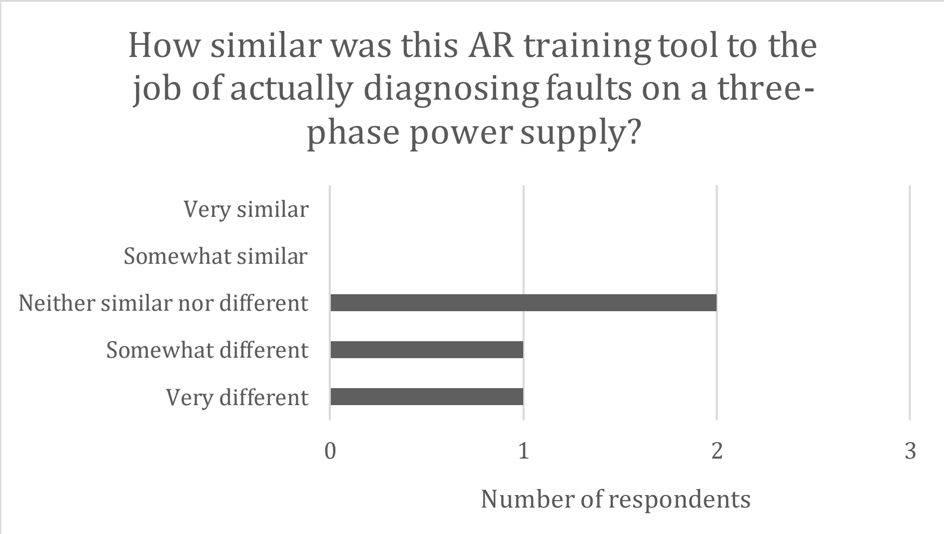


Chart 8.6 - Responses to the question 'How similar was this MR training tool to the job of actually diagnosing faults on a three-phase power supply?' by the 'expert' user group

Finally, all respondents were given the opportunity to give freeform comments on how they found the task and any suggestions for the future. From the "expert" user group only one comment was left (Table 8.6).

Table 8.6 - General feedback from "expert" users

Category	Feedback
Instructions	More clear instructions as to what the task was would have been helpful. I felt that I was performing familiarisation activities and then found that it was the task. As a result, I feel that I recorded incorrect results.

From the non-expert group, several comments were left (Table 8.7).

Table 8.7 - General feedback from 'non-expert' users

Category	Feedback
UI	I like it as a whole, just more options to go back in case of error on the user interface.
UI	Pointer should move faster
Device	The proximity of the probe and the screen sensitivity when tapping
Device	Accurate manipulation of phone to see in better detail the placing
Device	A few bugs with the image display, e.g. multimeter knob was shifted to the upper left corner.
Instructions	Force a tutorial to begin perhaps starting with just connect the dots on a white page, then build up to the image of the circuit
Instructions	Some sort of confirmation of the probes being placed correctly may help. Perhaps a sound cue or notification.
Instructions	At first I thought I had to drag the 2 circles with my finger on the screen, rather than move my device, maybe attaching a short video to illustrate this operation with the instructions would be helpful.
Device	I had an issue with the screen flickering so it was hard to aim. Aim in general was hard. Also, the menu would help if it was constantly there since navigation was sometimes unclear. More labels to the processes and steps would be helpful

These comments could be summarised into 3 main categories:

- *User interface difficulties (2) – e.g., pointer, options to go back a step*
- *Instructions/tutorial could be improved (3) – confirmation of input, tutorial to practice*
- *Device specific issues (4) – flickering screen, display errors, phone obstructs view*

8.4 Summary

Trial 5 presented a Mixed Reality training tool, with the aim of exploring the use of digital methods to supplement traditional teaching of vocational education. The motivation for this was to fill the chronic skills gap present in the UK engineering industry. This is in partial fulfilment of **Research Objective 4 - To explore novel methods of incorporating MR technologies into engineering training and education**.

As a proof of concept, a diagnostic task using a three-phase power supply was selected as an example, and a MR web application and printed diagram of the equipment were used to simulate the process of fault diagnosis. The tool was tested by comparing user performance, measured via four different metrics, amongst those who were experienced at the diagnostic task, and those who had no background in electrical engineering at all and were guided by additional MR content. The raw results tables can be found in Appendix F.5. By comparing performance between these two groups, conclusions could be drawn about whether MR guidance could be used to upskill novice workers in the engineering industry.

While the results presented in Section 8.3 certainly suggest that mixed reality training of this kind could be a beneficial tool, caution must be applied when interpreting these results. Due to COVID-19 restrictions during the research period, no direct comparison could be made to an actual physical version of the task; therefore, questions could be raised as to whether either of the virtual scenarios was truly representative of the industrial environment.

The mean task time was 65% faster for guided non-experts, but only at a confidence level of 90% as opposed to the more desirable standard of 95% confidence. As these experiments took place independently in the participants' homes, without supervision, certain anomalies were present in the data. For example, participant ID 467 was disregarded from the analysis due to having exceptionally long gaps between steps (over 1 h, when most took less than 15 min to complete the entire task). Without having observed the experiment, it is impossible to say whether this was an issue with the application, a home internet failure, or any number of other distractions in the user's personal life. In this case, the time gaps were so extraordinarily long that it seems safe to assume that some external issue came into play. However, in other responses recorded, shorter time gaps (2–3 min) occurred, and it is difficult to say if participants were genuinely taking so long to complete the step or if some other factor had come into play. This is a known issue and one of the main drawbacks of carrying out remote virtual research (Ratcliffe et al., 2021). In the analysis, these gaps were treated as pertinent to the research. However, this cannot be known for sure, so when restrictions on in-person studies are more lenient, it may be beneficial to repeat this study under closer observation. Given the uncertainty in measurement of the results, this is not ideal but indicates potential and makes the case for further investigation when in-person studies are permitted, and the reliability of the measured variables can be improved.

The percentage of faults correctly diagnosed saw similar results, with a 79% improvement in accuracy seen in guided non-expert users, but only an 85% significance level. Again, this is much less than the preferred value of 95%, so it should not be considered significant based on the results of this study but may warrant further investigation with a larger sample size. Additionally, though guided non-experts performed better, neither group scored perfectly, with 58% accuracy in the non-expert group and just 30% in the expert group.

The NASA-TLX score was also calculated using survey results. Comparison of means suggested that the non-expert users found the task less taxing overall than the expert users. This is in agreement with Masood and Egger's study (Masood and Egger, 2020), which found a decrease in NASA-TLX scores when using wearable AR to assemble a gearbox, and confirms that the AR task guidance has potential to be a valuable tool in training and familiarising new users with electrical systems. However, a two-sample t-test revealed that the differences found between expert and non-expert groups had limited statistical significance for the number of observations taken and for the NASA-TLX scores. This may be representative of a lack of effectiveness of the application, but it may also be the result of a limited sample size, making it difficult to robustly detect smaller differences in the data. Therefore, it is strongly recommended that future investigations into this technology aim to recruit a larger sample size than the 19 participants considered in this study.

A learning effect of sorts can be noted, as users appeared to make diagnoses faster during their fourth sub-task than in their first. This was especially true in the "non-expert" user group. However, accuracy decreased in the latter attempt, suggesting a fundamental lack of understanding of how the application worked, particularly in the case of the "expert" users using the app without additional guidance. This cannot be known for certain, as the study was carried out remotely in the users' homes, so no visual observations could be made—another limitation of the remote experimental approach.

This sense of confusion over how to operate the app was confirmed by the qualitative feedback, where one-third of the feedback remarked upon the instructions/tutorial given at the start of the study. Other key difficulties highlighted included some small inconsistencies in how the app was presented across different devices and some suggestions for how user interaction could be improved—no comments suggested the underlying idea or functioning of the app were problematic, however.

To enable the application of these new technologies in learning environments, digital competence of teachers is a key success factor. After all, students cannot benefit from new technologies if teachers do not have the skills to support digital resources and experiences. Following a study of more than 750 teachers in Spain, Pozo-Sánchez et al. (2020) concluded that, while most teachers had adequate levels of information literacy, communication and collaboration, one of the areas in which they lacked skills was creation of digital content. However, digital literacy does appear to improve at later educational stages (Sánchez et al., 2020), so it is likely that many educators working at an apprenticeship level may have better digital skills than their primary school counterparts. Nevertheless, to fully exploit the benefits which MR blended learning can offer, it is imperative that either a wide-reaching program to upskill educators with more digital skills is implemented or, more feasibly, that simple content authoring tools are developed to allow content creation with minimal coding experience.

One final limitation of the work presented here is that it does not measure long term learning effects, only short-term ability to follow instructions. Therefore, it should be beneficial in future to carry out a similar experiment with added repetition, with and without AR instructions, to explore if MR tools achieve this result via true learning or simply by delivering more information to the user in the virtual instructions.

In conclusion, the results of this study initially seem promising, with improved average values across all metrics measured in the MR-guided, non-expert user group, as opposed to unguided expert users. However, deeper investigation suggests these results do not meet the standard threshold of 95% significance. Due to the methodological limitations, resulting largely from the remote nature of COVID-era research, these results warrant further investigation to determine if MR can indeed be a valuable alternative to in-person learning for trainees in engineering and manufacturing. In addition, whilst this technology has much value to add in the vocational learning space, future studies should make comparisons to the users carrying out the task on real equipment to check the level of realism in the replication. It would also be advantageous to use a larger sample size, such that smaller differences between groups can be reliably detected if they exist.

Future studies should also include a focus on the long-term learning effect to see if MR users can put their learning into practice by repeating the task without guidance after a period of delay between learning and testing. If these initial results hold true when deployed on a larger scale, however, MR remote training could be an excellent way to reduce pressure on scarce resources, such as training facilities and educators' time. It would allow vocational learners to rehearse practical tasks in advance of accessing these resources, gain confidence, and make the most of their in-person contact time. Of course, this is of particular relevance during the COVID-19 pandemic, when the resulting restrictions mean access to these facilities is even more limited than usual. However, even beyond this, there is significant value in these technologies, as they can increase the amount of time users can spend rehearsing and perfecting practical tasks or potentially reduce the amount of contact time required with low-availability training facilities. This in turn has potential to mitigate the impacts of the pandemic, or possible future disruptions, to the learning process on the significant skills gap facing the engineering industry. Another possible extension of the concept presented here could be to link the simulated task to a recorded data stream from a turbine's digital twin and thus enable project-based learning using real asset data. This would further enhance the trainees' experience by allowing them to demonstrate their skills with a real industrial problem in a convenient and low-risk environment.

9 Use of AR to Enable the Factories of the Future

9.1 Introduction

This chapter presents Trial 6, a small-scale study in which AR is proposed as a method of on-the-job training, to reduce the time taken to familiarise shop floor workers with new technologies. This, along with Trial 5 (Chapter 8) is to address **Research Objective 4 - To explore novel methods of incorporating MR technologies into engineering training and education**.

Under Industry 4.0, smart and reconfigurable factories are predicted to become increasingly popular, allowing manufacturing businesses to be more flexible in both scale and variety of production at a moment's notice (ElMaraghy, 2019). To achieve this, it must be possible to quickly alter the set-up of any machinery and equipment.

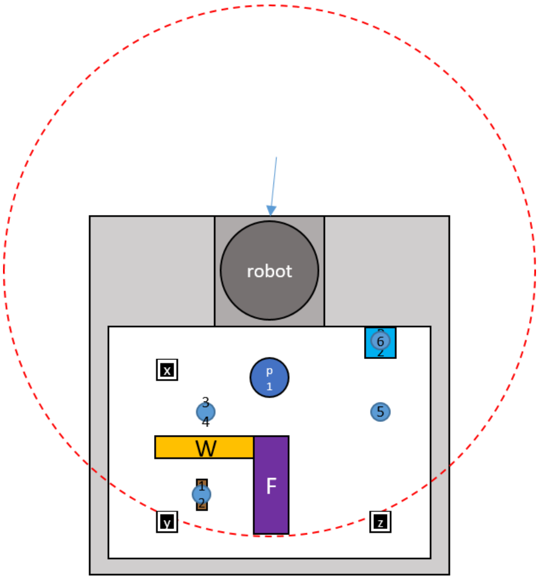
At the same time, another key technological change has also been taking place – the evolution of collaborative robotics, and as the manufacturing industry adopts the tools and principles of Industry 4.0 more widely, there is a need to upskill the existing workforce to operate these new technologies confidently and competently. Collaborative robots, or cobots, are specifically designed to interact with and work alongside humans. As such, they are often force and speed limited, so that they may operate in close contact with humans, negating the need for large robot cells for protection, and typically contain an array of sensors to help detect and prevent collision and injury (Peshkin and Colgate, 1999). They are also designed with simplicity of operation in mind, meaning they can be programmed and operated without writing a single line of code.

In this chapter, it is proposed that AR could be used as an enabling technology to allow even novice users to reconfigure robotic motion paths quickly and accurately without physical access to the industrial environment, enabling rapid, efficient changeovers in the modular factories of the future. In Trial 6, AR was used to model virtual obstacles that the operator must use as guidance when programming the robot to perform a simple pick and place operation. This mimics an industrial scenario in which a brand-new user is able to step up and program a motion path without the need for physical access to the actual work environment.

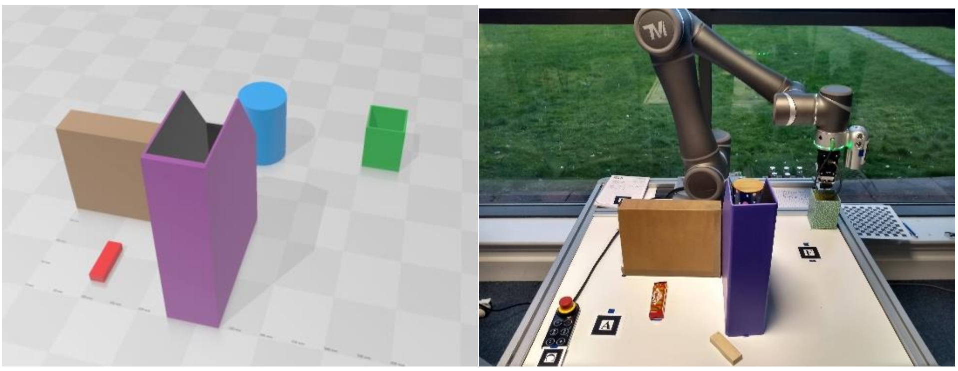
This type of AR instruction may be of use when planning and programming motion paths before a facility is fully built, or in the case of rapidly reconfigurable factories where the space may still be in use in its current layout and future set ups required advance planning to enable prompt changeovers. It may also reduce the number of people physically required to interact with the production environment, which is of particular benefit in the post-COVID world.

9.2 Task Selection and App Design

A TM5-900 Cobot arm (Omron, 2018) was used in this task, fitted with a custom pick and place gripper, as shown in Figure 9.1 (c).



(a)



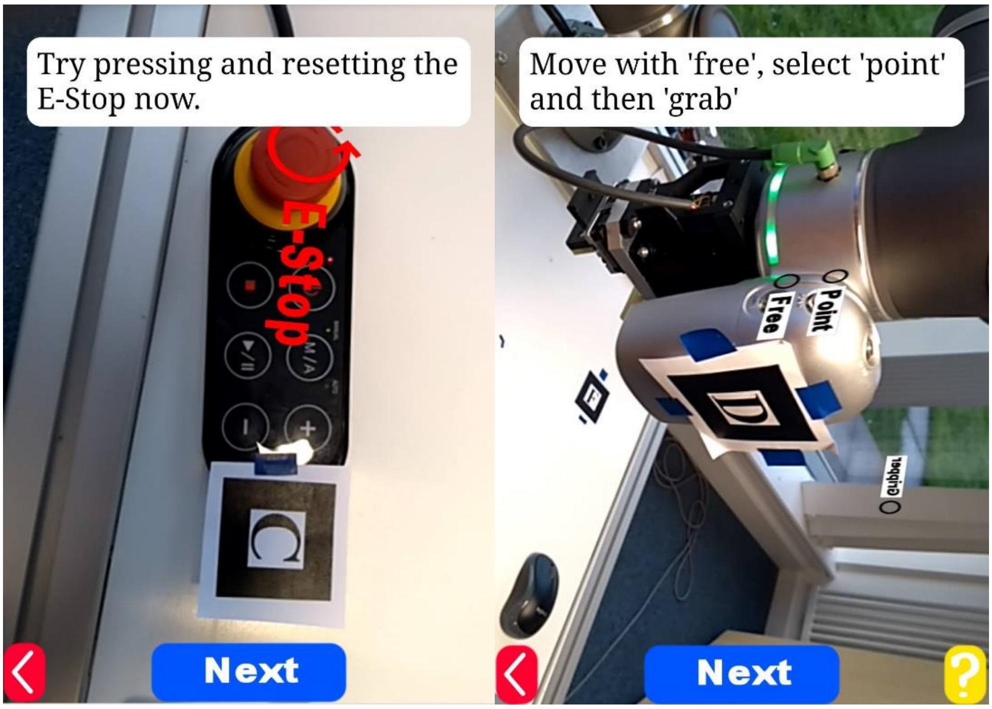
(b) **(c)**

Figure 9.1 – (a) Plan view diagram of robot layout and working area, (b) virtual models of the obstacles and (c) real version of the obstacles in situ next to TM5-900 Cobot

The TM5-900 can be programmed either via the **Windows Icons Mice Pulldowns (WIMP)** interface on screen using flowcharts, or by physically manipulating the end effector of the robot arm to the required position and saving it to a path using buttons built into the robot head. In this task, users were directed to program the robot via physical manipulation, a simpler and easier process for absolute beginners.

Participants were asked to program a motion path for the robot in which the arm was used to pick up a target object (caramel wafer), carry it to a predefined end, and release it from the grip of the robot to land in a container. Within the working volume of the Cobot arm there were a number of virtual obstacles to be avoided, loosely simulating a virtual factory layout.

An AR application was designed using web technologies as described in Section 5.2.1. Text boxes on screen contained task descriptions and instructions to the user on how to complete each step of the task, while 2D annotations drew attention to which buttons to press on both the robot stick and the robot arm itself (Figure 9.2).



(a) (b)

Figure 9.2 – Screenshots from the instructional app showing AR content overlaid onto (a) the robot stick, and (b) the Cobot arm

Once the set-up was complete, users could view the virtual obstacles using markers A and F on the baseboard. A combination of text-based instructions and 2D annotations directed users to avoid the objects when planning their path. They could then direct the robot to pick up the target object, carry it to the end and release, by physically manipulating the robot end effector from point to point, and saving those key points to form a motion path (Figure 9.3).

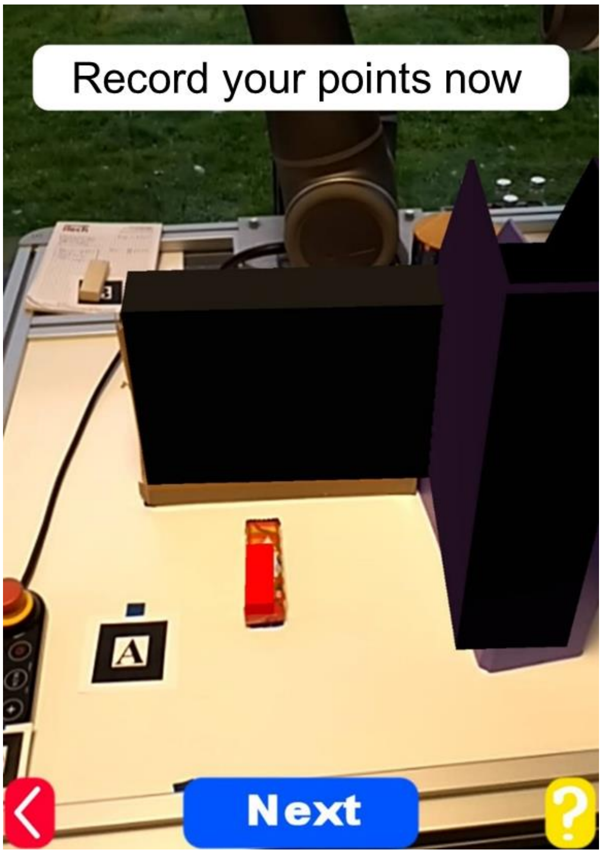


Figure 9.3 – Screenshot from the instructional app showing virtual obstacles overlaid onto the real world

Once this step was complete, users could press play on the robot stick to watch the robot move through the chosen path and review it against the AR content to check they were satisfied with the path. If they were pleased with their attempt, real objects were placed in the same locations as the virtual obstacles and the motion path was replayed to check the accuracy of the path. Users were permitted to make a second attempt if desired.

9.3 Methods

As a proof of concept, a sample of 12 participants were gathered for Trial 6 through convenience sampling on site at Booth Welsh's headquarters. It was important to carry out this study on the premises of an industrial environment.

While the work in Trials 0 – 5 (Chapters 5 – 8) gathered valuable information, the studies were limited in relevance as they were carried under relatively controlled conditions, an situation which is unlike that of the planned end user – field engineers and technicians. Therefore it was important that Trial 6 was carried out using actual industrial equipment and participants with an engineering background, in order to understand the challenges and opportunities presented by the industrial environment.

Participants are referred to from this point onwards only by anonymous participant IDs, a 3-digit number starting with a 6 (i.e., 6XX) to denote participation in Trial 6. A larger sample size may have been preferable, however the company were operating on a skeleton staff, with very few personnel physically on site and inviting more people on site exclusively for the purpose of this research was not an acceptable risk given the restrictions in place at the time. Further detail on health and safety measures taken, including risk assessment and safe system of work, are in Appendices G.1 - G.3.

On entry to the room, a brief explanation was given of the purpose of the study and directed users to follow the on-screen AR instructions to complete the task. While the author was on hand in case of any problems, minimal intervention was given except for technical issues and/or minor questions.

Users planned and programmed a motion path around the specified obstacles, first with only the virtual representations to judge their progress. Then the motion path was checked against the physical objects. If there were any errors or collisions, participants were offered the opportunity to try again. However most declined as they were constrained by time afforded away from their jobs.

Finally, participants filled out a post-experiment questionnaire. This was done online on the user's own devices, to minimise time spent in the same room as other people for risk management purposes. Because of this, the response rate was only eight out of twelve as once participants had left the room as there was limited control over their actions.

There were three main performance indicators considered in these experiments: overall task time, cognitive load of the task (as measured by the NASA-TLX questionnaire after the experiment) and outcome of the task.

Task outcomes were categorised as follows:

- **Success** = the operation was considered a success if the target was transferred from the start point to the end without touching any obstacles.
- **Partial success** = target was transferred from start to finish but brushed against the obstacles without colliding.
- **Failure** = collisions occurred, and/or the target was not transferred to the end.

The factors investigated in this chapter are summarised in Table 9.1, along with their abbreviated names:

Table 9.1 – Description and shorthand for dependent variables in this chapter

Task Completion Time	Time in seconds from start of task to completion	**TCT**
Error Rate	Number of errors (whether corrected or uncorrected) made during the task	**ER**
Cognitive Load	Mental effort required to complete the task, measured using the **NASA-TLX** scale (Hart and Staveland, 1988)	**TLX**

9.4 Results of Trial 6

Chart 9.1 shows the distribution of time taken to complete the Cobot programming task by each participant. It also shows whether they were successful in completing the task, partially successful, or failed to achieve the objectives of the task.

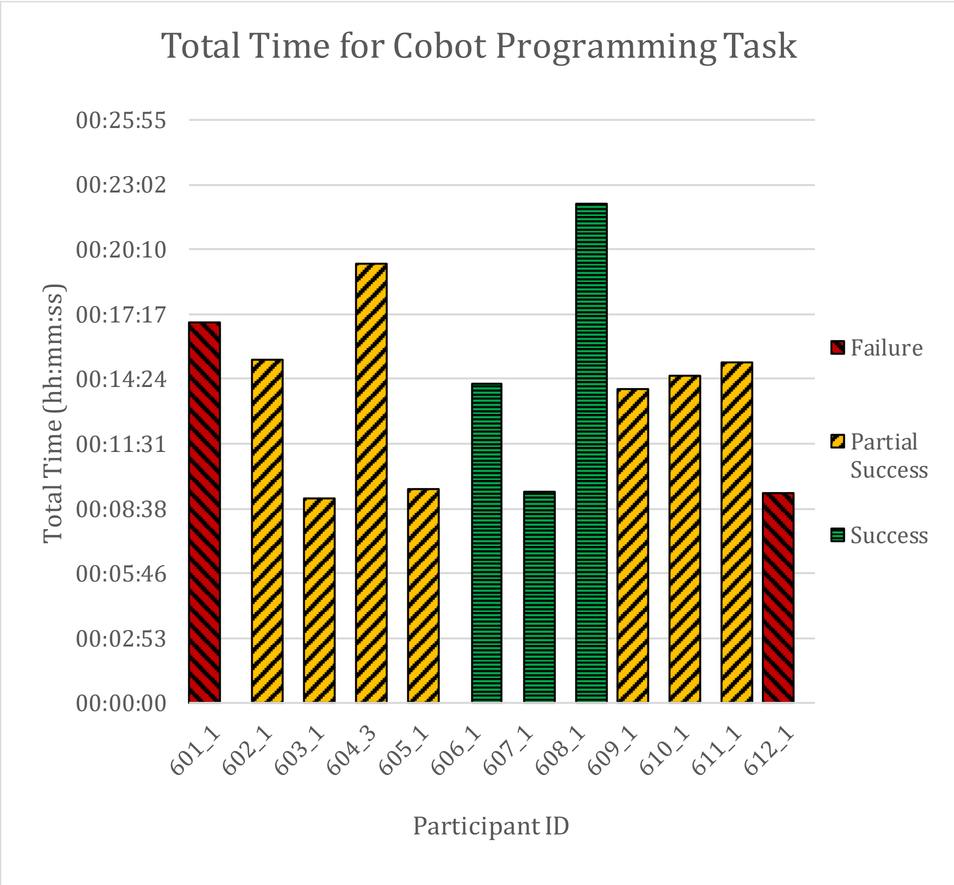


Chart 9.1 – Time taken by each participant to complete the Cobot programming task

As well as time and success rate, a post-task survey gathered data on cognitive effort involved in the task, using the NASA-TLX scale. These results are summarised in Table 9.2 (pg. 224).

Table 9.2 – Summary of time and NASA-TLX Scores for the Cobot Programming Task

		Average	S.D.
All	Time (hh:mm:ss)	00:14:06	00:04:03
	TLX Score	5	3
Success	Time (hh:mm:ss)	00:15:16	00:05:16
	TLX Score	5.25	0.25
Partial Success	Time (hh:mm:ss)	00:13:52	00:03:21
	TLX Score	4.42	4.132278
Failure	Time (hh:mm:ss)	00:13:08	00:03:47
	TLX Score	4.58	1.75

Successful participants took 11% more time on average than those who made errors, though it is worth noting the relatively small sample involved. Those who were partially successful rated the task as most cognitively demanding, followed by those who were successful, while those who failed found it least demanding – this is shown more clearly in Chart 9.2.

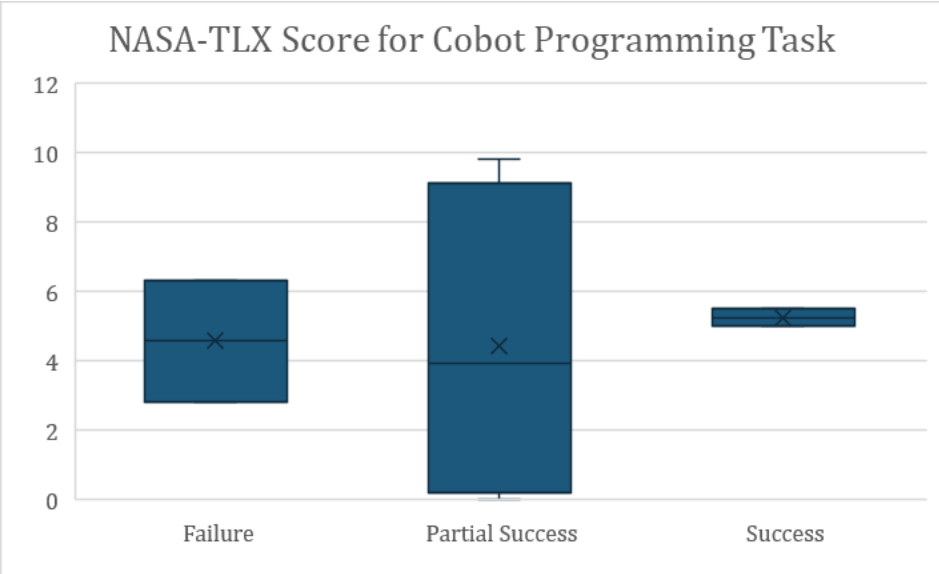


Chart 9.2 – NASA-TLX scores during the Cobot programming task, by on task outcome

Next, qualitative data from freeform comments in the survey was considered. A copy of the questionnaire may be viewed in Appendix G.4. Seven out of the eight participants who responded to the question "Do you think you made any errors whilst completing the task?" said yes – suggesting a level of self-awareness and understanding of the task aims.

These self-reported errors fall into three main categories (full results in Appendix G.5):

- *Robot manipulation difficulties (3)*
- *Didn't follow the instructions properly (2)*
- *Unfamiliar with functioning of robotic arm (2)*

9.5 Summary

In Trial 6, an AR guidance app delivered via mobile device allowed complete novices to accomplish relatively complex tasks in the field of digital manufacturing with little to no prior explanation, thereby answering **Research Objective 4 - To explore novel methods of incorporating MR technologies into engineering training and education**.

Using AR guidance, 10 out of 12 participants were able to complete the pick and place operation with some level of success, with the longest one taking under 23 minutes from start to finish. As a baseline comparison, typical training time for robot programming can be as long as 5 days (MTC Training, 2021). Of course, this type of training course would be very in-depth and include much trouble shooting and more complex functions than simply path planning so it is not a direct comparison. However, it is still significant that in a matter of minutes, 83% of users were able to program a pick and place task with partial or complete success having had zero prior knowledge of robotic programming.

Assessing cognitive effort of those taking part showed that those who did make errors were aware of them. This implies the instructions gave a clear indication of the task and criteria for success. As users were aware they made mistakes, it would have been ideal to allow them another attempt to see if they could correct them. This option had low uptake due to time constraints, but the learning effect demonstrated in Chapter 7 would suggest this is a possibility, at least for those who cited improperly following the AR instructions as the cause of their errors. Those who were unfamiliar with the functioning of the Cobot and who struggled to manipulate it may also benefit from increased familiarity with the hardware – showing that one limitation of AR guidance is that, being a primarily visual technology, it provides little information on how physically interacting with the environment will feel.

There are of course limitations to this kind of research – namely that there is no comparison made to novice users without AR instructions. This is suggested as an area for future research. Further, this is clearly a limited and isolated use of the Cobot and many operations in the manufacturing environment are more complex than this. However, this proof of concept does show promise that AR guidance can be used to make training more effective, thereby reducing the time taken for training. Though this may only be reasonable for occasional users of robotic systems as a much more thorough understanding of the underlying systems is necessary for robotics engineers. Another limitation is that participants completed the post-task surveys on their own devices, after leaving the room. This resulted in a reduced number completing the survey, so feedback is limited.

This method of Cobot programming could have applications for accelerating basic training of Cobot users, though it is likely more useful for the occasional user. While more regular users would certainly require more in-depth training including trouble shooting and more complex operations. However, the real benefit that this study highlights is the potential of AR for use in the reconfigurable factories of the future, by allowing intuitive path planning and collision/near-miss detection for even novice users without physical access to the plant layout in question.

10 Conclusions and Future Work

The aim of the research was to investigate how Augmented Reality technologies can be deployed effectively in manufacturing and engineering to improve performance.

The primary contribution to knowledge is an understanding of what makes an industrial AR instructional application successful, in terms of both definition of key performance measures and identifying how user interaction factors impact on said performance measures. Secondary contributions include the development of a standard task for comparing performance between different instructions designs, and an investigation of how AR technologies can be used in novel ways to benefit the engineering industry.

This was achieved through the following objectives:

Research Objective 1 To develop a flexible cross platform AR research tool which can operate using a variety of user interaction modes

Research Objective 2 To determine the most effective way of presenting AR procedural instructions for a simulated industrial task

Research Objective 3 To investigate the effect of learning and novelty on performance when following AR instructions

Research Objective 4 To explore novel methods of incorporating MR technologies into engineering training and education

Section 10.1 summarises the major conclusions of the research, and how they answer each of the four objectives. Section 10.2 discusses the implications of the main research findings and their potential impact on industrial applications. Finally, 10.3 discusses the limitations of the research, and suggestions for future research that would make valuable contributions to the field.

10.1 Summary and Conclusions

Chapter 2 examined the literature, revealing an opportunity for high quality experimental work to explore how UI factors in AR instructions affect user performance. The literature strongly suggested that MR was also a promising technology to help with practical education in manufacturing and engineering, particularly in the wake of the global pandemic. This led to selection of the aims and research objectives laid out in Section 2.8. In Chapter 353, four key performance indicators were selected to define good performance, based on the literature and industrial feedback via a survey. This led to the consideration of not only process output (time and accuracy), but also user acceptance, a very important factor in new technology adoption. Then, a standard task was selected, to compare performance. This was a short assembly task using Lego bricks chosen for its simplicity and low experimental cost, which allowed many repetitions and variations within the experiment.

Research Objective 1: To develop a flexible cross platform AR research tool which can operate using a variety of user interaction modes

In Chapter 5, an AR instruction application (app) was developed to work across multiple platforms and could easily change UI factors while maintaining the overall look and feel, thereby answering Research Objective 1. Additionally, Trial 0 served as a preliminary study to check the functionality of the app and assess the experimental methods laid out in Chapter 4.

Research Objective 2: To determine the most effective way of presenting AR procedural instructions for a simulated industrial task

This app and methodology were then used in Trials 1-3 (Chapter 6) to answer Research Objective 2 in detail:

- *Paper instructions were completed faster than AR overall, but AR instructions were rated as more usable. This was especially true for the wearable device.*
- *No significant differences were found based on how users interacted with and controlled AR content.*
- *On mobile devices, in-situ videos resulted in fewer errors and so are the recommended option. However, this was not the case for the head worn device, where text-based annotations were rated as more highly usable.*
- *No significant differences were found in the data based on age or gender, though it should be noted that the demographics of participants in Chapter 6 skewed towards 'young, educated male' so sample sizes of other categories were small.*

Research Objective 3: To investigate the effect of learning and novelty on performance when following AR instructions

In Chapter 7, Trial 4 was designed to build on these findings in order to answer Research Objective 3. There was a significant and rapid learning effect when using AR instructions, resulting in:

- *A 53% reduction in average task time over just five attempts.*
- *No significant difference found in terms of accuracy.*

Research Objective 4: To explore novel methods of incorporating MR technologies into engineering training and education

In Trials 5 and 6 (Chapter 8 and 9), two possible applications of MR in engineering training and education were developed and tested. Trial 5 used a MR tool to guide learners through a simulated fault diagnosis process on a 3-phase power supply, using only equipment available to online learners (i.e. a mobile phone and a printed diagram). Compared to unguided, experienced users, novice users following MR guidance:

- *Diagnosed 65% faults faster*
- *Faults were found 79% more accurately and*
- *29% less cognitive effort was required*

Finally, in Chapter 9, a proof of concept study, Trial 6, showed how AR could be used to guide novice users through the process of robotic path planning, without physical access to the target location.

- *Ten out of the twelve users completed the task either partially or completely successfully with as little as 8 minutes of instruction.*
- *Total training time was as little as 23 minutes of instruction or less.*

Whilst Studies 5 and 6 are not without their limitations (discussed in Sections 8.4, and 9.4), they give some idea of how XR technologies can transform the field of remote learning, with particular respect to vocational and practical training in the wake of the COVID-19 pandemic.

10.2 Industrial Relevance

Overall, web-based AR has many advantages in industrial training and instruction, as opposed to the perhaps more traditional game engines for building AR applications. With the rapid pace of change in technologies at this time, that cross platform compatibility is the key to making lasting AR apps. Therefore, using web-based tools that can be accessed on any device with a browser and camera is the simplest way to achieve this, while allowing you to upgrade your hardware any time you find one that better suits your needs. Of course, web-based AR has its limitations, and will still require updating when hardware changes significantly to take better advantage of, for example the enhanced hand tracking technology discussed earlier. Equally, there can be some compatibility issues with certain web browsers and operating systems, and the diverse nature of this software makes thorough testing a difficult challenge. However, generally, game engine developed apps encounter many of these issues too, and on balance it seems the positives outweigh the negatives. However, the most important factor when choosing a development platform if someone is developing an app in-house is probably existing skills within the company - the best solution is the one that can be maintained. If this is not a factor, for example if development and maintenance is outsourced to a third party, then web apps are recommended in most scenarios.

From the research presented in this thesis, it is clear that the best way to display instructions depends largely on the environment and the task. To some extent this is seen in the differing results from the literature review (Chapter 2) and even more so in the results of Trials 1-3 (Chapter 6) where it was shown that key factors in app design (interaction method for example) had little direct impact on user performance. Therefore, when considering implementing an AR guidance system in industry, thorough analysis of the target task should be carried out. Under laboratory conditions in Trials 1-3, no significant effect on performance was observed regardless of how users were controlling and interacting with AR content (Section 0), so it is recommended that interaction methods should be decided based on environmental factors. For example, in a workshop with many machining tools, where noise levels are high, it makes little sense to be using voice commands. Similarly, in the construction industry, PPE sometimes includes rigger gloves that would be inconvenient to remove them to operate a touchscreen, and may even make gesture control difficult, so in this case a voice command might be the preferred solution. Whatever the decision, those implementing AR can be confident it will not negatively influence user performance based on the experimental findings in Chapter 6.

Continuing the topic of AR devices, mobile or tablet AR is preferred as standard, as these performed better in Trial 3 (Section 6.5). This is certainly true for simple tasks in relatively clean, safe environments where users can pick up and put down a phone without too many concerns. As well as performing better in the studies in Section 6.5, they are an almost ubiquitous technology, very affordable, and many companies have already invested in 'work phones' for their employees. For smartphones, in-situ videos are recommended as an excellent way of conveying task information. This is especially true if the task involved not only physical manipulation, but also interaction with a PC screen or similar, as with the Cobot task in Trial 6 (Chapter 9), as it allows the use of screen captures from the computer to create a seamless experience.

Not all tasks are so well suited to mobile AR. As several participants noted in Trial 6, jobs where two hands are required for most or the entire task would benefit more from wearable devices. The same is true for dirty or dangerous job sites, where leaving a mobile phone on the workbench beside the user may be undesirable. Returning to the issue of interaction modes, these types of tasks may also be better suited to voice control if noise levels allow, maintaining the hands-free operation. When wearable devices are used, it is recommended to use text-based annotations to convey instructions, as this was shown to be most effective in Trial 6.

Due to the learning curve associated with the technology (demonstrated in Trial 4); AR is not always the best solution for very short repetitive tasks. Regular non-augmented workers could learn these quickly, so it is unlikely to overcome the learning curve associated with AR before they have simply memorised the task. However, if AR is already being used for other parts of the workday, it may well be desirable to extend it to all sub-tasks regardless for the sake of consistency, and because the learning curve will have already been overcome when adjusting the AR for the other task elements. Additionally, as Funk et al. (2015a) found, AR can be beneficial to those who have memory trouble or other cognitive difficulties, even for very short tasks.

Building on the idea of the AR learning curve, if task completion time is important to the operation, then allowing those new to AR to carry out a few simple, low stakes tasks to adjust to the UI before using on real tasks is very valuable. Trial 4 shows that task completion time decreased rapidly with practice, so allowing just a few minutes to become familiar with the UI could save a lot of time in the future.

AR can also have many roles in education and training in the post-COVID world. This may be by supplementing classroom/online learning to be more immersive and representative of the work environment as in Trial 5 (Chapter 8), or by enhancing on-the-job training to allow less support by more experienced workers as in Trial 6 (Chapter 9).

From Trial 6, where a tool is presented to guide users through a Cobot programming task, there is definite potential for these web based tools to reduce training time and cost, at least to convey basic knowledge and skills, even if more in depth teaching and training is needed for advanced learners.

Moreover, when it comes to enhancing vocational education, AR has potential to be an excellent tool to make learning more engaging, as shown by Trial 5 where a Mixed Reality tool for a fault diagnoses task is shown as an example. Trial 5 shows the potential of MR to enable remote learning of practical tasks using low cost and widely accessible technologies. As well as providing temporary assistance to vocational learners during the COVID-19 pandemic, this technology can also provide many benefits and should be considered as a supplement to traditional education methods even as the world returns to normal in future. MR learning experiences such as this have potential to reduce pressure on scarce facilities across a range of educational settings – from labs and workshops to the replication of future workplaces – by giving learners a better baseline knowledge before accessing facilities or equipment for the first time. As learners can access content asynchronously, learning is made more flexible and accessible, which opens training options to those who would otherwise find strictly scheduled classes difficult to attend. This may include fulltime workers trying to upskill in their spare time, people who work hours outside of the traditional 9-5, or those with additional caring responsibilities who may find it difficult to cover caring duties for larger periods of time that traditional college and university education typically requires.

10.3 Limitations and Future Work

The work presented in this thesis is not without its limitations. Moreover, during the research, several additional ideas for research were inspired that could not be included in the scope of this project. Therefore, this section makes recommendations for future work to address methodological concerns, and to expand upon the scope of the ideas presented here.

Some methodological limitations are common to all the experimental work presented in Chapters 6 - 9. This includes limited diversity in the samples of volunteers who undertook the experimental tasks. As participants were gathered via convenience sampling at Strathclyde University's engineering department, the sample was skewed to over-represent highly educated young men, which is not necessarily typical of the target population (offshore technicians) and certainly not an accurate representation of the general population. While the Trial 3 (Section 6.5) showed no difference based on demographic factors, the limited numbers of some groups mean that it may well be a lack of evidence rather than a lack of response.

> ***Recommendation 1:*** *It would be beneficial to repeat Trials 1-3 with a sample more representative of the target group i.e. wind turbine technicians*

Section 6.5.3 also explored the effect of age and gender on performance. Though no significant differences were found, this may have been a result of the limited demographics of the sample population.

> ***Recommendation 2:*** *Use the results of Trials 0-3 in future meta-analyses to assess the effects of age and gender on performance when following AR instructions.*

Another caveat is that due to the rapidly evolving technology in this field, even in the year since these studies were carried out, hand-tracking technology has improved dramatically. Full 6 degree-of-freedom finger tracking is now available as standard on some HMD devices which allows recognition of a much wider range of gestures. This could potentially make gesture recognition more robust, intuitive and overall a less frustrating experience, and therefore make a difference to the results of Chapter 6 where interaction method had minimal impact on performance. Further, 5G technology promises an era of low latency communications and connected networks of devices, making MR viable in a wider range of locations than ever, likely becoming more prevalent in field engineering. As this happens, the industry will likely gravitate more towards industrially focussed device instead of consumer applications, and a new range of safety rated devices may be on the horizon.

Trials 4-6 faced additional methodological challenges due to the COVID-19 restrictions in place at the time of research. Studies 4 and 5 took place remotely, which introduced uncertainty in the results, as there was a lack of direct observation of user behaviour. This was particularly true of error data, which was prone to under-reporting. Troubleshooting was also an issue once participants and the author were no longer physically co-located. Several participants dropped out of the study without completing the task, but without in-person support and real time conversations with participants, it was difficult to determine a cause for this. Despite these challenges, the research produced will be valuable to both industry and academia, In fact, the difficulties of the

COVID-19 pandemic went on to inspire the study on MR for vocational training presented in Trial 5 – resulting in new methods for making the education system more robust to societal disruption in future. Further research may be carried out to examine how this compares to traditional training methods, and how knowledge is retained in the long term.

> ***Recommendation 3:*** *Draw comparisons between the performance of guided novices with a) experts, b) those recently trained by a person, and c) those recently trained only in the classroom.*

> ***Recommendation 4:*** *Measure the long-term learning effect associated with MR learning tools, by repeating the study several days or weeks after the initial training period and comparing performance with and without additional AR guidance.*

While the initial results in Trial 5 showed great potential in improving learner's ability to successfully complete a simulated maintenance task, there is not yet confirmation that it is a good or accurate representation of the physical environment in question, as implied by the post-task survey results in 8.3. Some users also provided feedback and suggestions on how the layout of the app could be improved and noted some technical difficulties when operating the MR instructions.

> ***Recommendation 5:*** *User feedback from 8.3 should also be taken on board to improve the learning experience, such as giving clearer indication of when the new instruction is loaded.*

Recommendation 6: *The study could also this could be expanded further to include real data from live engineering assets, to further enhance vocational education with experience of solving real industrial problems.*

Similarly, while Chapter 8 focusses on the example of engineering apprentices, it could be used throughout **STEM** education. Consider the example of a university student, where both technicians and time in workshops and laboratories are often at a premium. Of course, this is of particular importance during a pandemic, but these constraints remain, though to a lesser extent, even without such an event.

Recommendation 7: *Using MR alongside a textbook insert, similar to the methods used in used in Trial 5 may allow students to practice using complex equipment at home and in their own time, leading to more efficient use of limited time on site.*

Recommendation 8: *Trial 6 could be expanded to allow users more attempts at the task, to confirm whether the learning effect found in Chapter 7 does indeed exist in a more industrial task.*

In conclusion, there are many avenues for research yet to be explored – from expanding the original studies, to verifying the results in industrially relevant scenarios, to exploring new use cases for AR in training and learning. However, this thesis presents a significant contribution to the understanding of how User Interaction factors affect user performance in industrial assembly tasks, as well as providing proof of concept studies for how novel AR solutions may be applied in the field of engineering training.

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Appendix A. Performance Measures

A.1 Performance measures in each paper

Paper	Question	Measures
(Müller et al., 2019)	NASA-TLX	Mental Demand Physical Demand Temporal Demand Performance Effort Frustration
	Confidence in selecting correct target	Accuracy
	Willingness to use	Willingness to use
	Qualitative feedback	open
	accuracy	Accuracy
	task completion	TCT
(Funk et al., 2015b)	GATM components	t_locate_part t_pick t_locate_pos t_assemble
	errors	ER
	NASA-TLX	Mental Demand Physical Demand Temporal Demand Performance Effort Frustration
(Radkowski and Ingebrand, 2017)	easily understand and follow instructions (Likert)	Instructions easy to understand
	The instructions shown though the display were helpful. (Likert)	Instructions helpful
	The HoloLens is convenient to wear.(Likert)	Convenient to wear
	I feel confident that I performed well in completing this task.(Likert)	Confidence in performance
	I would recommend the HoloLens to other people as visual instruction device (Likert)	Recommend to others
	The HoloLens is fun to work with. (Likert)	Fun
	I looked past the HoloLens's display to assemble the piston motor (Likert never-often)	Looked past display to object

	I had to move my head often to completely see and understand the instructions (Likert never-often)	Head movements
	Free discussion	open
(Hou and Wang, 2013)	TCT	TCT
	Errors	ER
	NASA-TLX	Mental Demand Physical Demand Temporal Demand Performance Effort Frustration
	Assembly attempts until error free completion	Number of attempts
(Jetter et al., 2018)	COG1: How much perceptual activity is required?	Perceptual activity
	COG2: How much mental activity is required?	Mental Demand
	COG3: How hard do you have to work to accomplish the use case?	Hard work
	SPAT1: Using Bosch CAP would support me enormously in identifying a component of interest among a cluster of components	Identification of points of interest
	SPAT2: Using the Bosch CAP would improve my ability to distinguish components in a reliable manner	Distinguish components
	SPAT3: Using the Bosch CAP would reduce errors in identifying the correct position of components	Positioning errors
	RTE1: Using the Bosch CAP would reduce errors in installing/fixing components	Installation errors
	RTE2: Using the Bosch CAP would reduce errors caused by insufficient data/information available.	Data errors
	RTE3: Using the Bosch CAP would reduce time for task completion.	TCT
	RTE4: Using the Bosch CAP would reduce time for rework (rectification of executed work).	Rework
	PEOU1: It seems to be feasible to learn how to operate the BOSCH CAP.	Easy to learn
	PEOU2: Handling the tracking/scan function is intuitive.	Intuitiveness
	PEOU3: I find the Bosch CAP is appropriate for my work environment.	Appropriate to work environment

	PEOU4: I found the Bosch CAP worked stably and reliable.	Reliability
	PU1: Using the Bosch CAP would enable me to complete my task with higher quality.	Quality of performance
	PU2: Using the Bosch CAP would enhance my effectiveness for my job.	Effectiveness
	PU3: Using the Bosch CAP would make it easier to do my job.	Ease of job
	PU4: I would find the Bosch CAP to be useful in my job.	Usefulness
	AT1: Using the Bosch CAP in my job would be a good idea.	General approval
	AT2: I am positive about the Bosch CAP.	Positive reception
	BI1: Assuming I have access to the Bosch CAP, I intend to use it.	Willingness to use
	BI2: Given that I have access to the Bosch CAP, I predict that I would use it.	Likely to use
	BI3: I would recommend the Bosch CAP to my colleagues	Recommend to others
(Henderson and Feiner, 2011)	Ease of use (Likert)	Ease of use
	satisfaction level (Likert)	Satisfaction
	Intuitiveness (Likert)	Intuitiveness
	Rank techniques by intuitiveness	Intuitiveness
	Comment on each condition	open
	List additional technologies that might assist with roles	Suggest additional tech
(Aromaa et al., 2018)	QUIS (smiley faces)	Terrible/wonderful Difficult/easy Frustrating/Satisfying Inadequate power/adequate power Dull/Stimulating Rigid/flexible Reading characters on screen Highlighting helpful Organisation of info is clear Sequence of screens is clear Use of terms is consistent Terminology related to task Message position consistent Informed about computer tasks Error messages helpful Easy to learn Trial and error exploration is easy Memorability

		Tasks clear Messages on screen helpful Supplementary materials clear System speed System reliability System noise Correcting mistakes easily Experience/inexperience taken into account
	SUS	Would like to use frequently Complexity Ease of use Requires technical support Functions well integrated Inconsistency Easy to learn Cumbersome Confidence in performance Learning curve
	TAM	Ease of use Usefulness
	Development ideas for system (interview)	Suggest additional ideas
	Suitability for maintenance work (interview)	Appropriate to work environment
	How it would change the work (interview)	How it would affect work
	Thematic analysis of interview responses	open
(Kim and Irizarry, 2020)	Demographics	gender age familiarity
	SUS	Would like to use frequently Complexity Ease of use Requires technical support Functions well integrated Inconsistency Easy to learn Cumbersome Confidence in performance Learning curve
	SMEQ	Mental Demand
	co-presence questionnaire	co-presence
	rank conditions by preference (+ opinions)	Preference
	TCT	TCT
	frequency of hand gestures/sketch cues	Hand gestures

	Interview comments	
(Voit et al., 2019)	SUS	Would like to use frequently Complexity Ease of use Requires technical support Functions well integrated Inconsistency Easy to learn Cumbersome Confidence in performance Learning curve
	AttrakDiff (hedonism)	Pleasure
	ARI questionnaire (immersion)	Interest Usability Emotional attachment Focus of attention Presence Flow
(Hou et al., 2013)	pre-task mental rotation quiz to judge cognitive capacity	Cognitive capacity
	errors	ER
	NASA-TLX	Mental Demand Physical Demand Temporal Demand Performance Effort Frustration
	number of trials before error free assembly	Number of attempts
(Krichenbauer et al., 2018)	miles test (ocular dominance)	Ocular Dominance
	comfort (1-10)	Comfort
	TCT	TCT
	head motion	Head movements
	mouse motion	Mouse movements
(Fiorentino et al., 2014)	TCT (log-10 transformed)	TCT
	errors	ER
	ease of use (Likert)	Ease of use
	satisfaction level (Likert)	Satisfaction
	intuitiveness (Likert)	Intuitiveness
(Gimeno et al., 2013)	accuracy (Likert)	Accuracy
	efficiency (Likert)	Efficiency
	learnability (Likert)	Easy to learn
	memorability (Likert)	Memorability
	satisfaction (Likert)	Satisfaction

	would use in future	Likely to use
	need less precious knowledge	Need for knowledge
	more intuitive	Intuitiveness
	more accurate	Accuracy
	faster	Speed
	I've felt more comfortable	Comfort
	general satisfaction	Satisfaction

A.2 Table of Performance measures

Factor	Number of occurrences in the 16 papers	How its measured
TCT	6	**Measure**
Easy to learn	6	Likert/QUIS/**SUS**
Ease of use	6	Likert/**SUS**/TAM
Mental Demand	6	**TLX**/SMEQ/Likert
Performance	5	Measure/**TLX**/Likert
Intuitiveness	5	Likert/**ranking**
Physical Demand	4	**TLX**
Temporal Demand	4	**TLX**
Effort	4	**TLX**
Frustration	4	**TLX**
Accuracy	4	Likert/**Measure with ER**
open	4	**Freeform comments**
ER	4	**Measure**
Confidence in performance	4	**Likert**
Satisfaction	4	**Likert**
Would like to use frequently	3	**SUS**
Complexity	3	**SUS**
Requires technical support	3	**SUS**
Functions well integrated	3	**SUS**
Inconsistency	3	**SUS**
Cumbersome	3	**SUS**
Learning curve	3	**SUS**
Willingness to use	2	Likert
Recommend to others	2	Likert
Head movements	2	Measure
Number of attempts	2	Count
Appropriate to work environment	2	**Likert/interview**
Usefulness	2	Likert/TAM
Likely to use	2	Likert
Memorability	2	QUIS/Likert
t_locate_part	1	**GATM**
t_pick	1	**GATM**
t_locate_pos	1	**GATM**
t_assemble	1	**GATM**
Instructions easy to understand	1	Likert
Instructions helpful	1	Likert
Convenient to wear	1	Likert
Fun	1	Likert
Looked past display to object	1	Likert
Perceptual activity	1	Likert
Hard work	1	Likert
Identification of points of interest	1	Likert
Distinguish components	1	Likert
Positioning errors	1	Likert
Installation errors	1	Likert
Data errors	1	Likert
Rework	1	Likert
Reliability	1	Likert
Quality of performance	1	Likert
Effectiveness	1	Likert

Ease of job	1	Likert
General approval	1	Likert
Positive reception	1	Likert
Suggest additional tech	1	List
Terrible/wonderful	1	QUIS
Difficult/easy	1	QUIS
Frustrating/Satisfying	1	QUIS
Inadequate power/adequate power	1	QUIS
Dull/Stimulating	1	QUIS
Rigid/flexible	1	QUIS
Reading characters on screen	1	QUIS
Highlighting helpful	1	QUIS
Organisation of info is clear	1	QUIS
Sequence of screens is clear	1	QUIS
Use of terms is consistent	1	QUIS
Terminology related to task	1	QUIS
Message position consistent	1	QUIS
Informed about computer tasks	1	QUIS
Error messages helpful	1	QUIS
Trial and error exploration is easy	1	QUIS
Tasks clear	1	QUIS
Messages on screen helpful	1	QUIS
Supplementary materials clear	1	QUIS
System speed	1	QUIS
System reliability	1	QUIS
System noise	1	QUIS
Correcting mistakes easily	1	QUIS
Experience/inexperience taken into account	1	QUIS
Suggest additional ideas	1	Interview
How it would affect work	1	Interview
gender	1	Demographics
age	1	Demographics
familiarity	1	Demographics
co-presence	1	co-presence questionnaire
Preference	1	Rank/comment
Hand gestures	1	Measure

Appendix B. Augmented Reality for Maintaining Offshore Wind

B.1 Copy of Survey

Introduction

My name is Eleanor Smith, I am a PhD student at the University of Strathclyde, working in collaboration with industrial partner Booth Welsh. If you have any questions or concerns regarding this research, please contact me at eleanor.smith@strath.ac.uk

What is the purpose of this investigation?

This survey forms part of my PhD research into how Augmented Reality (AR) might be used to improve maintenance of offshore wind turbines, by assessing the potential benefits or problems AR may bring to the offshore maintenance industry.

This project is part of the wider Renewable Engine INTERREG VA programme, which you can read more about here.
This project in particular is a collaboration between the Advanced Forming Research Centre (AFRC) at the University of Strathclyde, and industrial partner Booth Welsh.

About This Survey

Thank you for taking the time to fill out this survey today, it should take no more than **10 minutes** to complete. Responses will be collected until **5pm** on **Friday 07/09/2018**.

Please take some time to read the participant information on the next screen before proceeding to the main body of the survey.

Page Break

Participant Information

Do you have to take part?

No, participation in this survey is voluntary. If you decide at any point during the survey that you no longer wish to take part, simply close the window and your responses will not be recorded.
Why have you been invited to take part?

I am looking for participants working in the fields of offshore wind, onshore wind, and/or industrial maintenance. If you do not meet these requirements but feel you have some other relevant experience or knowledge to offer, please fill out the survey too but understand your response may or may not be included in the final analysis.

Page Break

Privacy Notice

Introduction

The University of Strathclyde is committed to transparency and to complying with its responsibilities under data protection legislation. This privacy notice sets out important information regarding how we will use your information and your rights under the legislation. It is important that you read this notice prior to providing your information.
The University of Strathclyde is a data controller under data protection legislation. Any enquiries regarding data protection should be made to the University's Data Protection Officer at dataprotection@strath.ac.uk

What is personal data/personal information?
In simple terms, personal data is information which identifies and relates to you, either on its own or in conjunction with other information held by the University.
Special Categories of Personal Data is personal data which falls into one of these categories:
Personal data revealing racial or ethnic origin, political opinions, religious or philosophical beliefs, trade membership; genetic data; bio-metric data for the purpose of uniquely identifying a natural person; data concerning health; data concerning a natural person's sex life or sexual orientation; data relating to criminal convictions/criminal proceedings.

The types of personal information we collect
We collect identifiable information about you, such as name, organisation and contact details. You can decide to omit details if you desire.
Privacy notices, like this one, tell you what the information will be used for. If we are ever collecting sensitive personal data, as defined above, additional safeguards will be in place around how we can use that data.

How we use personal information
The personal data you supply here will be used to contact you with regards to further discussion of AR and the offshore maintenance industry, although this is optional.
The legal basis for this processing of your data under GDPR is Consent.

Marketing
The data you provide to this system will not be used for direct marketing to you.

Where we store and process personal information
Electronic personal data is held on the University's secure servers. Hard copy data will be stored securely to prevent unauthorised disclosure.

How we secure personal information
The University has robust Information Security policies in place the protect all the data it holds, including your personal data. You can read more about these policies and technical standards on the University website https://www.strath.ac.uk/staff/policies/informationsecurity/

Who we share data with
This data is not normally shared outwith the University - though vital interests or legal obligations may require it to be released to e.g. public agencies.

How long will we keep your data
The identified retention period for your data covered by this privacy notice is 12 months. After which it will be reviewed, and if the purpose for which it is being processed is still valid, the retention period may be extended. If however your data has served its purpose then your personal data will be securely destroyed. Sometimes data will be stored for longer periods e.g. for archiving purposes in the public interest, scientific or historical research purposes. Non-personal data may be kept indefinitely depending on needs.

Your rights under the General Data Protection Regulations
You have a number of rights under the Act. These include:
The right to be informed, the right to access, the right to rectification, the right to erasure, the right to restrict

processing, the right to data portability, the right to object, rights in relation to automated decision making and profiling.
For more information on your rights, please see https://ico.org.uk/for-the-public/is-my-information-beinghandled-correctly/

Right to access personal data
You have a right to request a copy of the information the University holds about you; this is known as a 'Subject Access Request' (SAR). For more information see the University's Data Protection web pages or contact dataprotection@strath.ac.uk

Right to complain
If you have any concerns/issues with the way the University has processed your personal data you can contact the Data Protection Officer at dataprotection@strath.ac.uk. You also have the right to lodge a complaint against the University regarding data protection issues with the Information Commissioner's Office (https://ico.org.uk/concerns/).

Keeping your information up to date
You can update your details at any time prior to publication by contacting: dmem-adminteam@strath.ac.uk

Status of this Privacy Notice
This privacy notice is subject to change. The University will advise you of any significant changes you need to be aware of, in relation to this privacy notice. This Privacy Notice was last reviewed on 11/07/2018.

End of Block: Survey Introduction

Start of Block: Consent

Do you agree to take part in this survey, according to the terms outlined in the Participant Information on the previous screens?

○ Yes (1)

○ No (2)

End of Block: Consent

Start of Block: Respondent Details

Which organisation do you represent?

____

Q6 Which area does your organisation mainly operate in?
(Select all that apply)

▢ Onshore Wind (1)

▢ Offshore Wind (2)

▢ Industrial Maintenance (3)

▢ Other (please specify) (4) ____

Q7 Which of the following best describes your role within your organisation?

◯ Technician (1)

◯ Business Development (2)

◯ Management/Leadership Team (3)

◯ Manufacturing Engineer (4)

◯ Training Manager (5)

◯ Other (please specify) (6) ____

Q8
To the best of your knowledge, does your organisation currently use Augmented Reality in any capacity?

For the purposes of this survey, please consider Augmented Reality (AR) to be any device or technology which enhances the real world with virtual information (such as text, diagrams, animation, CAD models) directly in the user's line of sight. This may include a range of devices, such as head up displays, smart glasses, tablets, and mobile devices.

◯ Yes (1)

◯ No (2)

End of Block: Respondent Details

Start of Block: If your organisation does NOT use AR...

Q9 Please select the main reasons you think your organisation does not currently use Augmented Reality?

- Benefits are unclear (1)
- Implementation costs (2)
- Lack of necessary skills in the company (3)
- Lack of knowledge about AR (4)
- Concerns over technology dependence (5)
- Health and safety concerns (7)
- Site specific restrictions (provide brief summary if possible) (6) ____

End of Block: If your organisation does NOT use AR...

Start of Block: If your organisation does use AR...

Q9 Please select which Augmented Reality device(s) are used in your organisation?

- Android Mobile (1)
- Android Tablet (2)
- Daqri Smart Glasses or Helmet (3)
- Google Glass (4)
- iPad (5)
- iPhone (6)
- Meta HMD (7)
- Microsoft Hololens (8)
- Don't know (9)
- Other (please specify) (10) ____

Q10 Which AR software (if known) does your organisation use?

____

Q11 Please give a short description of the types of tasks for which your organisation uses Augmented Reality?

____

Q12 To your knowledge, has your company encountered any issues or challenges when implementing Augmented Reality?

____

End of Block: If your organisation does use AR...

Start of Block: Benefits/Limitations

Q13 Listed below are some possible concerns or limitations relating to the use of Augmented Reality in industrial maintenance.
Please rate how important you consider them to be, in the context of your work.

	Extremely important (1)	Very important (2)	Moderately important (3)	Slightly important (4)	Not at all important (5)
Implementation costs (1)	▢	▢	▢	▢	▢
Physical safety of workers using AR (2)	▢	▢	▢	▢	▢
Data protection/cybersecurity (3)	▢	▢	▢	▢	▢
Over reliance on technology (4)	▢	▢	▢	▢	▢
Current technology not mature enough (5)	▢	▢	▢	▢	▢
Legal issues/liability (6)	▢	▢	▢	▢	▢
Connectivity (7)	▢	▢	▢	▢	▢
Health and Safety (8)	▢	▢	▢	▢	▢

Q14 Listed below are some likely benefits of using Augmented Reality to guide industrial maintenance. *Please rate how important these possible improvements would be to your organisation.*

	Extremely important (1)	Very important (2)	Moderately important (3)	Slightly important (4)	Not at all important (5)
Reduced time locating items (such as instructions, components) (1)	▢	▢	▢	▢	▢
Reduced error rate (2)	▢	▢	▢	▢	▢
Improved task completion time (3)	▢	▢	▢	▢	▢
Reduced need for one-to-one training (4)	▢	▢	▢	▢	▢
Easy communication with off site experts (5)	▢	▢	▢	▢	▢
Better capturing of maintenance records/data (6)	▢	▢	▢	▢	▢
Partial automation of record-keeping to reduce paperwork (7)	▢	▢	▢	▢	▢

Q15 Listed below are some possible features which Augmented Reality applications may include.
Please rate how useful these features would be to your organisation.

	Extremely useful (1)	Very useful (2)	Moderately useful (3)	Slightly useful (4)	Not at all useful (5)
Individual user log-ins to control access (1)	▢	▢	▢	▢	▢
Live video/audio communication (2)	▢	▢	▢	▢	▢
Automated capture of sensor data and activity logs (3)	▢	▢	▢	▢	▢
Displaying 3D models in the context of the real working environment (4)	▢	▢	▢	▢	▢
Displaying text-based information directly in line of sight (5)	▢	▢	▢	▢	▢
Hands free operation (6)	▢	▢	▢	▢	▢

Q16 Which types of task do you feel could most benefit from Augmented Reality?
(Check as many as are applicable)

- Machining/industrial (1)
- Locating items (2)
- Assembly/dis-assembly (3)
- Routine maintenance (4)
- Reactive or unplanned maintenance (5)
- Training (6)
- Identifying non-compliance, or variation from design (7)
- Guided diagnosis of faults (8)
- Other (please specify) (10) ____

Q22 If you would like to make any more comments about AR, turbine maintenance, or related technologies, please enter them below.

____

End of Block: Benefits/Limitations

Start of Block: End of Survey

If you have any further comments of questions, please contact me at eleanor.smith@strath.ac.uk.
On the next screen, you will be directed to a separate survey where you may provide some contact details if you wish to hear more about the project, or be involved further. This is optional, and contact details will be recorded separately to the rest of your responses to retain anonymity.

Thank you.

B.2 Survey Results

Q4 - Do you agree to take part in this survey, according to the terms outlined in the Participant Information on the previous screens?	
Yes	45
No	1

Q5 - Which organisation do you represent?	
Proserv	1
Ventient Energy	1
Equinor	1
DCU	1
Strathclyde	2
SSE	1
Vattenfall	1
SGRE	10
Wartsila	1
SoXSA	1
Black & Veatch	1
Innogy Renewables	2
Offshore/onshore turbine services	1
Iberdrola	1
Doosan	1
EDF	2
BVG Associates	1
Natual Power	1
Everoze	1

Q6 - Which area does your organisation mainly operate in?(Select all that apply)	
Onshore Wind	20
Offshore Wind	22
Industrial Maintenance	4
EDUCATION	1
offshore platform maintenance	1
Space applications	1
Water and Renewables	1

Q7 - Which of the following best describes your role within your organisation?	
Technician	3
Business Development	3
Management/Leadership Team	12
Manufacturing Engineer	2
Training Manager	0
Analyst	1
Lecturer	1
Public Relations	1
Operation and maintenance engineer	1
Engineer	1
Director	1

R&D Engineer	1
Research Engineer	1
Operation and Maintenance Engineer	1
Wind park control operations Analyst	1
Project Engineer	1

Q8 - To the best of your knowledge, does your organisation currently use Augmented Reality in any capacity?

Yes	16
No	19

IF NO:		IF YES:	
Q9 - Please select the main reasons you think your organisation does not currently use Augmented Reality?		**Q9 - Please select which Augmented Reality device(s) are used in your organisation?**	
Benefits are unclear	6	Android Mobile	2
Implementation costs	7	Android Tablet	2
Lack of necessary skills in the company	1	Daqri Smart Glasses/Helmet	0
Lack of knowledge about AR	11	Google Glass	2
Concerns over technology dependence	0	iPad	9
Site specific restrictions	3	iPhone	2
Health and Safety Concerns	1	Meta HMD	1
		Microsoft HoloLens	3
		Proserv owned IP	1
		Scada	1
		Q10 - Which AR software (if known) does your organisation use?	
		Proserv owned IP software	
		hololens	
		Samsung 3d goggles	
		Wind Dialogue	
		No	
		Matterport	
		None	
		Q11 - Please give a short description of the types of tasks for which your organisation uses Augmented Reality?	
		Asset Integrity Monitoring	
		VIP trips	
		identification description of equipment, links to drawings/documents - early prototype	
		For public engagement to allow users to get an immersive experience of working on an offshore wind farm	
		Mainly training and familiarisation with the WTG. Customer relationships and location of failing sensor in the WTG	
		Monitoring	
		Project Specific AR for Tower and Transition Piece Mock Up. Used for clarification of installed systems and reference.	
		None	
		Remote engineering and public acceptability	

	Ipads used by technicians during service to reference checklists, manuals, diagrams etc Design
	Q12 - To your knowledge, has your company encountered any issues or challenges when implementing Augmented Reality?
	No Don't know None, but we ensure that people sit down and are aware of the risks, such as motion sickness No None, but we ensure that people sit down and are aware of the risks, such as motion sickness No

ALL:

Q13 - Listed below are some possible concerns or limitations relating to the use of Augmented Reality in industrial maintenance.Please rate how important you consider them to be, in the context of your work.

	Implementation costs	*Physical safety of workers using AR*	*Data protection/ cybersecurity*	*Over reliance on technology*	*Current technology not mature enough*	*Legal issues /liability*	*Connectivity*	*Health and Safety*
Extremely Important	14	15	6	1	4	4	8	15
Very Important	6	5	5	4	10	3	9	3
Moderately Important	3	2	10	9	7	10	3	6
Slightly Importnant	1	1	3	7	2	5	3	1
Not Important At All	0	1	0	3	1	2	1	0

Q14 - Listed below are some likely benefits of using Augmented Reality to guide industrial maintenance.Please rate how important these possible improvements would be to your organisation.

	Reduced time locating items	*Reduced error rate*	*Improved task completion time*	*Reduced need for on-to-one training*	*Easy communication with off site experts*	*Batter capturing of maintenance records/data*	*Partial automation of record-keeping to reduce paperwork*
Extremely Important	11	11	12	6	10	13	10
Very Important	12	12	9	6	10	8	11
Moderately Important	0	0	3	10	2	1	3
Slightly Important	0	0	0	0	0	1	0
Not Important At All	1	0	0	2	1	1	0

Q15 - Listed below are some possible features which Augmented Reality applications may include.Please rate how useful these features would be to your organisation.

	Individual user log-ins to control access	*Live video/audio communicatio n*	*Automated capture of sensor data and activity logs*	*Displaying 3D models*	*Displaying text-based information*	*Hands free operation*
Extremely Useful	8	6	7	10	6	10
Very Useful	7	10	9	9	13	9
Moderately Useful	8	7	5	4	3	4
Slightly Useful	2	0	2	1	2	0
Not Useful At All	0	0	0	0	0	1

Q16 - Which types of task do you feel could most benefit from Augmented Reality?(Check as many as are applicable)

Machining/industrial	5
Locating items	11
Assembly/dis-assembly	11
Routine maintenance	16
Reactive or unplanned maintenance	17
Training	16
Identifying non-compliance, or variation from design	8
Guided diagnosis of faults	18
H&S Analysis of hazards inside the WTG	1

Q22 - If you would like to make any more comments about AR, turbine maintenance, or related technologies, please enter them below.

not my area

Unless augmented reality becomes part of an OEMs training programme it will not be widely utilised. Training is primarily dictated by turbine OEM for technicians, or under the Gwo canopy. Under Gwo, training mimics the conditions suitably enough for the purpose it serves. Offshore familiarisation is valuable, and as cost effective as augmented reality is in terms of flexibility of tasks covered. For augmented reality to be taken on it needs to either be able to demonstrate a cost saving for maintenance and troubleshooting situations where there is high net value associated with an offshore trip, or demonstrate hands on benefits for hgih frequency tasks

We are very focussed on using new technologies to make our techs work safer, this could mean: reduce number of visits to WTG or create a physical barrier between tech and hazards or make techs aware of hazards not easily forseen. Safety is out priority and if AR is able to show a tangible benefit in terms of H&S it will really get a big push from the business

Appendix C. Trial 0: Preliminary Study

C.1 Consent and Participant Information for Trial 0

Participant Information Sheet

Name of department: Design, Manufacture, and Engineering Management
Title of the study: Industry 4.0 and Augmented the Millennial Worker

Introduction
You are invited to take part in a research study, exploring the effectiveness of Augmented Reality (AR) as a way of delivering instruction guidance. Before you decide if you wish to take part, it is important for you to understand the context of the research and what will be involved. Please take your time to read the following information carefully. If anything is unclear, please ask.
My name is Eleanor Smith (eleanor.smith@strath.ac.uk), I am a PhD student in DMEM at the University of Strathclyde, working with Booth Welsh as part of the EU funded Renewable Engine INTERREG project.

What is the purpose of this investigation?
This study forms part of my PhD research – 'Industry 4.0 and Augmenting the Millennial Worker'. In particular, this study aims to assess how to effectively convey procedural instructions in AR.

Do you have to take part?
No, participation is voluntary. Even if you decide to take part, you are still free to withdraw at any point and without giving a reason.

What will you do in the project?
In this study, you are invited to perform some assembly tasks, using either an Augmented Reality mobile application, or paper based instructions to guide you through the process. Prior to attempting the task, you will receive a short demonstration of how to use the application. There is no time limit on completing the task.

What information is being collected:
We will record how long it takes to complete the task and how many errors are made. Afterwards, you will be able to provide some feedback on the task via a very short questionnaire. No personal data will be collected, and all other data will be fully anonymised.

How will the information be stored?
In accordance with the university data management policy, this information will be stored anonymously on a secure university laptop and backed up on the university server. Results of the study may be published in appropriate peer-reviewed journals and conference publications.

What happens next?
Once you have read and understood the information above, and asked any, you may decide whether you wish to take part in this study. If you are happy to continue, please sign the consent form provided. If you do not wish to take part, thank you for your attention – you are free to leave.

Researcher contact details: Eleanor Smith, eleanor.smith@strath.ac.uk
Principle Investigator details: Paul Blackwell, paul.blackwell@strath.ac.uk

If you have any questions/concerns, during or after the research, or wish to contact an independent person for more information, please contact:
Secretary to the University Ethics Committee,
Research & Knowledge Exchange Services
University of Strathclyde,
Graham Hills Building,
50 George Street,
Glasgow
G1 1QR
Tel: 01415483707 Email: ethics@strath.ac.uk

Consent Form

Name of department: Design, Manufacture and Engineering Management
Title of the study: Industry 4.0 and Augmenting the Millennial Worker

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences. If I exercise my right to withdraw and I don't want my data to be used, any data which have been collected from me will be destroyed.
- I understand that anonymised data (i.e. .data which do not identify me personally) cannot be withdrawn once they have been included in the study.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project

(PRINT NAME)	
Signature of Participant:	Date:

C.2 Ethics Checklist

Ethics Committee -
Code of Practice on Investigations on Human Beings

When implementing a staff or student project which involves 'investigation on human beings' it is important to note that the university has a code of practice governing the implementation and conduct of such investigations. This 'code of practice was developed by the 'Ethics Advisory Committee' and approved by the university court on 5th May 2000. The code governs all investigations on human beings including class teaching experiments and demonstrations, student projects and research investigations which fall within the scope of the code. The 'Departmental Research Committee' will act as the 'Departmental Ethics Committee', and can approve most routine, non-invasive investigations.

It is the responsibility of the supervisor to make the student aware of relevant guidelines and ensure that they are observed. The supervisor is also responsible for submitting details of proposed investigations for approval where necessary.

The following contains 2 checklists to aid the implementation of this practice:

(i) The first is to identify cases which require to be approved by the University Ethics Advisory Committee. If any of the boxes are marked in checklist (i) the investigation must be submitted to the university committee for approval.

(ii) The second is to ensure correct procedure is adhered to in any 'routine or non-invasive' investigation i.e. those which are readily approved by the 'Department Ethics Committee' (in essence the checklist represents a summary of Section 6 of the Code of Practice on Investigations on Human Beings.)

These checklists should not be viewed as a substitute for the original document and thus all supervisors should be familiar with the code before utilising these in staff/student research projects. The checklists are designed to ensure that the staff/students are immediately aware of the implications of the guidelines to their investigation. Furthermore, they act as departmental records of staff/student conduct in investigations on humans.

As 'Ethics Advisory Committee' approval of a protocol can take up to 4 weeks (longer for very specific requests), where research is likely to include an element of 'investigations on humans', an analysis of expected procedures should be carried out at as early a stage as possible.

In addition to the university regulations, investigations of a Physiological, Sociological and Biological nature must conform to additional 'codes of practice' set out by relevant professional bodies - in such cases the secretary of the ethics advisory board can supply copies of these statements.

(i) Supervisor and Student Ethics Checklist

Project Title: Industry 4.0 and Augmenting the Millennial Worker

Participants (staff/students carrying out investigation): Eleanor Smith, Paul Blackwell (Supervisor)

Investigation Content: User evaluation of simple assembly guidance techniques

Does the investigation involve, any of the following (mark as appropriate):

1)	Harm, discomfort, physical or psychological risk (esp. pregnant women, elderly, the young).	yes ☐	no ☑
2)	Participants whose ability to give voluntary consent is limited (cognitively impaired, prisoners, persons with chronic physical or mental conditions).	yes ☐	no ☑
3)	Invasive techniques (DNA testing, collection of body fluids/tissue).	yes ☐	no ☑
4)	Extensive degree or duration of exercise or physical exertion.	yes ☐	no ☑
5)	Manipulation of human responses (cognitive or affective) which may involve stress or anxiety.	yes ☐	no ☑
6)	Administration of drugs, liquid/food additives.	yes ☐	no ☑
7)	Deception of the participants which might cause distress or effect their willingness to participate in the research.	yes ☐	no ☑
8)	The collection of highly personal, intimate, private or confidential information.	yes ☐	no ☑
9)	Payment to the participants (other than travel/time costs).	yes ☐	no ☑

If the answer to <u>any</u> of the above questions is yes you <u>must</u> submit a protocol to the 'Ethics Advisory Committee' unless previous consent has been granted for practising the 'generic' procedure involved. The protocol for such submissions to the 'Ethics Advisory Committee' can be found in Appendix A of the 'Code of Practice on Investigations of Humans Beings'.

~~Supervisors~~ Signature(s)

.... Date 5/2/19

.... Date ....

Students/Researchers Signature(s)

.... Date 30/01/19

.... Date ....

.... Date ....

.... Date ....

(ii) Checklist for Department Approved Investigations

Mark all boxes when you have read, understand and, where appropriate, will adhere to the guidelines - also note the documentation required relative to your investigation:

N.B Investigators must acknowledge, understand and adhere to all of the points on this checklist.

Project Title: ~~Augmented~~ Industry 4.0 and Augmenting the Millennial Worker

Participants (staff/students carrying out investigation): Eleanor Smith, Paul Bodwell (Supervisor)

Investigation Content: User evaluation of simple assembly guidance techniques

It is the supervisors responsibility to make students aware of these guidelines and the students to provide the supervisor with the required documentation from affected investigation components. Signed copies should be maintained by the supervisor and student(s) for departmental records.

- ☑ **Consent**. Obtain informed consent of all volunteers. A consent form must be signed by all volunteers.
- ☑ **Protection**. Protect all volunteers from possible harm and preserve their rights. No investigation should involve significant risks to mental or physical well-being of its participants.
- ☑ **Inducement**. Provide no financial inducement nor other coercion (actual or implied) to persuade people to take part in the investigation.
- ☑ **Withdrawal.** Volunteers must be free to withdraw at any stage, without giving reason.
- ☑ **Termination.** The investigation should stop immediately if volunteers report any problems (physical, mental or otherwise) during it. The problems must be reported to the appropriate ethics committee.
- ☑ **Recruitment.** Volunteer recruitment should wherever possible be via letter, notice (or orally - if through a group approach). However, random street or doorstep surveys are acceptable.
- ☐ **Staff Participation.** The motives for staff/students to participate as a volunteer in an investigation should be taken into special consideration i.e. neither declining nor agreeing to participate in an investigation should affect academic assessment in anyway.
- ☐ **Special Consideration**. Special consideration should be given to the young, adults with any cognitive disabilities or learning difficulties and to all persons who live in or are connected to an institutional environment (in such cases the investigator should refer to **Appendix C** of the 'code of practice on investigations on human beings').
- ☐ **Pregnancy.** Women of child bearing age must not be recruited for any investigation which could be harmful to fertility/pregnancy (in such cases the investigator should refer to **Appendix C** of the 'code of practice on investigations on human beings').
- ☐ **Selection.** Submissions based on the investigation should include details of the basis for volunteer selection i.e. questionnaires and/or other measures in the selection process.
- ☐ **Justification.** Investigators must justify the number/type of subjects chosen for each study.

☑ **Confidentiality.** Confidentiality and privacy must be maintained. Any waiver of confidentiality should be justified and consent must be given, in writing, by the volunteer(s). In addition, the investigator must comply with Data Protection Legislation.

☑ **Informing Volunteers.** Each volunteer must be provided with an information sheet providing full relevant details of the nature, object and duration of the proposed investigation and a contact for further queries (whom is independent of the investigation normally the secretary of the ethics advisory committee).

☑ **Deception.** There shall be no deception that might affect a person's willingness to participate in an investigation nor about the risks involved.

☑ **Unusual Symptoms.** Volunteers will be encouraged to note any unusual or unexpected symptoms arising during the investigation. These should be reported to the appropriate ethics committee

☑ **Location.** Places where investigations take place should be appropriate to the type and risk factor of study undertaken. Further, the ethics committee are entitled to carry out spot checks.

☑ **Records.** Full records of all procedures carried out should be maintained in an appropriate form. A register of all volunteers should be taken and a note of the population/sample from which they were drawn.

☑ **Queries.** Post investigation queries from a participant should be directed to an appropriate professional (supervisor, head of department etc.).

☑ **Insurance.** It is the responsibility for the applicant to seek extended insurance if the investigation scope falls out-with the University's Public Liability Policy (in such cases the investigator should refer to **Appendix B** of the original 'code of practice' document).

Additional general guidelines exist for biological, psychological and sociological investigations - in such cases refer to **Sections 6.2 and 6.3** of the original 'code of practice' document.

Supervisors Signature(s)

.... Date 5/2/17

.... Date ....

Students/Researchers Signature(s)

.... Date 30/01/19

.... Date ....

.... Date ....

.... Date ....

C.3 Full Results Table for Trial 0

ID	**Step No**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14						
002	**Time (s)**	0.0	21.7	34.2	41.1	63.3	70.8	107.3	112.7	125.6	131.3	145.8	152.1	162.3	167.5	176.6						
ID	**Step No**	0	1	2	3	2	1	2	3	4	5	6	7	6	7	8	9	10	11	12	13	14
003	**Time (s)**	0.0	117.1	146.1	203.1	203.2	208.6	211.3	220.5	227.3	236.9	269.8	277.2	279.7	286.6	298.9	308.3	329.6	337.3	354.5	361.9	375.3
ID	**Step No**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14						
004	**Time (s)**	0.0	89.2	113.5	121.8	127.5	131.5	153.4	165.6	176.8	179.7	186.4	190.1	206.8	212.1	216.4						
ID	**Step No**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14						
005	**Time (s)**	0.0	40.3	57.1	63.6	75.0	81.4	100.8	112.8	120.3	128.8	145.4	152.1	159.2	165.0	181.7						
ID	**Step No**	0	1	2	3	4	5	6	7	8	9	8	9	10	11	12	13	14				
006	**Time (s)**	0.0	50.5	73.1	88.0	99.2	108.5	165.4	172.6	192.7	199.7	226.3	251.3	268.3	272.9	290.5	295.0	308.9				
ID	**Step No**	0	1	2	3	4	5	6	7	6	7	8	9	10	11	12	13	14				
007	**Time (s)**	0.0	49.6	72.8	80.9	90.6	96.4	209.8	218.6	220.5	225.9	234.3	238.6	249.1	253.1	264.7	279.2	297.7				
ID	**Step No**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14						
008	**Time (s)**	0.0	49.7	61.0	68.5	80.9	88.6	104.0	109.4	117.5	125.0	134.6	150.5	158.8	165.9	176.7						
ID	**Step No**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14						
009	**Time (s)**	0.0	29.3	51.8	57.3	86.5	97.4	138.9	154.2	162.7	168.0	184.4	190.4	201.0	207.4	213.8						
ID	**Step No**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14						
010	**Time (s)**	0.0	31.3	43.7	58.5	70.8	78.6	98.5	104.5	112.8	119.6	150.1	155.9	165.4	181.3	188.0						
ID	**Step No**	0	1	2	3	2	3	4	5	4	5	6	7	8	9	10	11	12	13	14		
011	**Time (s)**	0.0	56.8	71.1	79.5	87.9	99.4	108.6	110.4	112.6	121.8	134.9	145.5	149.8	155.5	173.0	182.4	188.6	195.8	200.9		
ID	**Step No**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14						
012	**Time (s)**	0.0	115.2	130.4	136.8	146.3	153.3	161.3	171.7	180.0	184.0	190.8	194.4	199.4	201.8	208.6						
ID	**Step No**	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14						
013	**Time (s)**	0.0	49.9	57.0	61.5	68.3	74.0	83.2	86.6	92.0	95.7	107.8	110.4	116.2	119.5	124.0						

Appendix D. Studies 1-3: User Interaction in AR

D.1 Consent and Participant Information

Participant Information Sheet

Name of department: Design, Manufacturing and Engineering Management
Title of the study: Industry 4.0 and Augmenting the Millennial Worker
Introduction
You are invited to take part in a research study, exploring the effectiveness of Augmented Reality as a way of delivering instruction guidance. Before you decide if you wish to take part, it is important for you to understand the context of the research and what will be involved. Please take your time to read the following information carefully. If there is anything which is not clear of you would like more information, please ask.
My name is Eleanor Smith (eleanor.smith@strath.ac.uk), I am a PhD student in DMEM at the University of Strathclyde.
What is the purpose of this research?
This study forms part of my PhD research – 'Industry 4.0 and Augmenting the Millennial Worker' in which we aim to explore the use of Augmented Reality (AR) technology as a form of maintenance guidance. In this study, we are comparing user performance when following different types of AR and paper based instructions. Ultimately, the knowledge gained from these experiments will feed into research on how AR can best be deployed to support maintenance technicians working on offshore wind turbines. This research is part of the EU funded Renewable Engine INTERREG programme. This project is based at the Advanced Forming Research Centre (AFRC) with support from industrial partner Booth Welsh.
Do you have to take part?
No, participation is voluntary. If you decide to take part, you will be given a copy of this information sheet and asked to sign a consent form. Even if you decide to take part, you are still free to withdraw at any point and without giving a reason.
What will you do in the project?
You will be asked to complete a two short assembly tasks. For one of the tasks, paper instructions will be provided to guide you through the task, step by step. In the other task, you will be given digital instructions, via either a mobile device or a head worn display. Prior to completing these two tasks, you will have the opportunity to complete a short practise session, to familiarise yourself with the instruction format. You will also be asked to fill in a few short questionnaires, about your experience with the different instruction formats.
You are free to withdraw at any time and without explanation. If you leave the study early, your data will be deleted and not included in any analysis or publications.
Why have you been invited to take part?
We are looking for participants with normal or corrected-to-normal vision, who have the physical and cognitive ability to carry out a short assembly task according to a short list of instructions.
What are the potential risks to you in taking part?
There are no significant risks foreseen in taking part in this study. You may find some tasks challenging, but you will have the opportunity to practise before taking part in the main study. If at any time you feel distressed, please let us know right away. You are free to withdraw at any time and without explanation.

What information is being collected in the project?
Before the task, we will ask you a few questions about yourself to help understand the demographics of our participants in order to identify any potential biases in our results. During the tasks, data will be collected on how much time each step takes to complete, and if any errors are made. After each task, we will ask you some questions about how you found the experience. We will not ask you to provide any sensitive data, and all data will be stored against an anonymous ID so that your results are not identifiable in any future analysis and publications. If there are any questions you do not feel comfortable answering, you are not required to respond.
Who will have access to the information?
All information collected doing the study will be strictly confidential, and will only be available to people directly involved in the research project (i.e. the f and principal investigator).

Where will the information be stored and how long will it be kept for?
In accordance with the university data management policy, this information will be stored for 2 years, on a secure university laptop and backed up on the university server. Data will be stored such that it is only identifiable through the allocated participation code.
Thank you for reading this information – please ask any questions if you are unsure about what is written here.
What happens next?
Results of the study may be published in appropriate peer-reviewed journals and conference publications, however any information about you will be fully anonymised (name removed) so that you cannot be identified from it.
Once you have read and understood the information above, and asked any questions if you are unsure, you may decide whether you wish to take part in this study.
If you are happy to continue, please sign the consent form provided. If you do not wish to take part in the study, thank you for your attention – you are free to leave.
Researcher contact details: Eleanor Smith, eleanor.smith@strath.ac.uk
Chief Investigator details: Paul Blackwell, paul.blackwell@strath.ac.uk
If you have any questions/concerns, during or after the research, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:
Secretary to the University Ethics Committee
Research & Knowledge Exchange Services
University of Strathclyde
Graham Hills Building
50 George Street
Glasgow
G1 1QE
Telephone: 0141 548 3707
Email: ethics@strath.ac.uk

Consent Form

Name of department: Design, Manufacturing and Engineering Management
Title of the study: Industry 4.0 and Augmenting the Millennial Worker

- I confirm that I have read and understood the Participant Information Sheet for the above project and the researcher has answered any queries to my satisfaction.
- I confirm that I have read and understood the Privacy Notice for Participants in Research Projects and understand how my personal information will be used and what will happen to it (i.e. how it will be stored and for how long).
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences.
- I understand that anonymised data (i.e. data that do not identify me personally) cannot be withdrawn once they have been included in the study.
- I understand that any information recorded in the research will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project.

(PRINT NAME)	
Signature of Participant:	Date:

D.2 Pre-Experiment Survey

Pre-Experiment Questionnaire

Please answer the following survey honestly.

Take as much time as you need, and please ask the experimenter if you have any questions or concerns.

Aside from Participant ID, none of these questions are compulsory.

Remember, you are free to withdraw from the experiment at any point without giving a reason.

Participant ID:

[ ]

Age Group

What is your current age?

- ○ 16-25 years
- ○ 26-40 years
- ○ 41-65 years
- ○ 66 years and over
- ○ Prefer not to say

Gender

What gender do you identify with?

- ○ Female
- ○ Male
- ○ Prefer not to say
- ○ Other (please specify)

[ ]

D.3 Post-Experiment Survey

18/06/2019 Post Experiment Questionnaire

Post-Experiment Questionnaire

Please answer the following survey with regards to the task you have just completed.

Take as much time as you need, and please ask the experimenter if you have any questions or concerns.

Participant ID:

Which instruction type did you use?

- Head Mounted Display
- Mobile AR
- PDF

Mental Demand

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc)?
Was the task easy or demanding, simple or complex, exacting or forgiving?

Low (0) **High (100)**

Mental Demand: 50

Physical Demand

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc)?
Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low (0) **High (100)**

127.0.0.1:8080/nasa.html 1/4

D.4 Full Results Table

Participant ID	Device	Interaction	Display	age	gender	role	xp	tech	IT	Order	AR Condition TCT	ER	TLX	SUS	comments	Paper Condition TCT	ER	TLX	SUS	comments
108	hmd	native	cad	26-40	f	PhD Student	1	3		4p/ar	499.188	1	55.83333	65	I found this much more difficult than traditional pen and paper but I'm sure with practice accurate set up and regular use the use of this technology could improve on more traditional instructions	25.885	0	14.16667	10	The paper instructions were self explanatory and I felt comfortable using it
109	hmd	native	text	18-25	m	PhD Researcher	4	4		4p/ar	184.683	3	33.33333	65	the graphical instructions were good however it needs to be refined to better work in conjunction with the real world. The poor quality of the graphics could cause nausea if used for a long time. What could have worked best was if the next piece was highlighted in contrast to the pieces already laid down it would have been easier to distinguish the pieces.	81.26	1	20	10	Quite easy and straightforward to follow
110	hmd	native	video	26-40	m	Research Associate	1	4		4p/ar	94.599	1	25	47.5	heavy head set	66.179	0	21.66667	20	none
120	hmd	native	cad	18-25	m	PhD student from advanced power energy system	2	4		3ar/p	205.14	0	32.5	40	the angle of two eyes which different with people may makes losing calculation	35.126	0	43.33333	32.5	like just playing lego
112	hmd	voice	text	18-25	m	PhD Student	1	4		4p/ar	84.258	0	36.66667	42.5	n/a	36.622	0	30.83333	15	n/a
111	hmd	voice	cad	18-25	m	EngD Student	2	4		5p/ar	104.345	0	40	70	AR headset viewing range is too small	39.964	0	35.83333	22.5	n/a

113	hmd	voice	video	18-25	m	PGR Reasercher	3	5	5p/ar	292.491	1	40.83333	40	Perhaps the use of a plug in microphone into the laptop would resolve the voice command issues	37.996	0	25	27.5	Needed to regularly move head back and forth in order to follow instructions
121	hmd	native	text	18-25	m	PhD Student	2	4	4ar/p	96.998	0	28.33333	32.5	Some colours were difficult to see due to the low opacity of VR	30.699	0	39.16667	12.5	Feels like more movement was actually involved when reading from the PDF (i.e. head rotation to read etc.)
122	hmd	native	video	18-25	f	undergraduate student	2	4	3ar/p	501.609	1	9.166667	32.5	1	58.994	0	10.83333	20	the instructions on paper were harder than the VR instructions as they were in 2D. The 3D instructions made it easier to tell what way the lego should be facing.
138	hmd	native	cad	18-25	m	Innovation Manager	2	5	4p/ar	421.547	0	45.83333	55	The alignment was slightly off and it was difficult to identify what orientation the system was asking you to place the blocks in (especially the first box)	61.717	0	10	10	The only slight challenge from the paper instructions was the slightly different orientation of the instructions compared to the real environment. I rotated the test bench to rectify that.
142	hmd	voice	text	18-25	m	PhD student	1	4	4p/ar	596.707	0	20	17.5	The technology was good. It made positioning the blocks the correct way very simple and it was quick and easy to assemble the structure because of this	74.731	3	24.16667	15	Simple instructions but do not provide the full detail required for orientating the parts so you had to think about that though for a simple setup it was straight forward
123	hmd	voice	cad	18-25	m	PhD Student	1	4	4ar/p	400.468	1	14.16667	15	n/a	43.153	0	3.333333	20	n/a
125	hmd	voice	video	18-25	m	PhD student	1	4	4ar/p	222.599	0	22.5	40	ok	52.305	0	25	42.5	ok
139	hmd	native	text	26-40	m	Postgraduate Student at DMEM	3	5	3p/ar	279.511	1	55	55	Wider field of vision and specific room lighting might make this product much better.	43.241	0	10	25	None
140	hmd	native	video	18-25	m	Postgraduate researcher	1	3	4p/ar	78.107	0	33.33333	30		49.436	0	55	57.5	Requires a degree of spatial awareness to understand the

																			orientation blocks should be placed.
141	hmd	voice	cad	18-25	m	Student	1	3	4p/ar	116.702	2	55.83333	72.5	difficult to measure depth and different views	114.506	3	51.66667	27.5	Na
143	hmd	voice	video	18-25	m	PhD Student	1	3	3p/ar	436.492	1	41.66667	65	A	44.355	0	17.5	22.5	Time pressure felt highest before starting but became low after the first two pieces
146	hmd	native	video	26-40	f	Student part time library assistant part time nursery nurse	1	3	3ar/p	77.991	0	39.16667	45	Simple and fun	31.823	0	20	12.5	Very easy
147	hmd	voice	cad	18-25	m	Student.	3	4	4ar/p	106.695	0	24.16667	20	The technology work very well throughout and instructions were clear and easy to understand. The only issues were overlays not matching up with real world object perfectly. However this did not hinder progress. And certain colour were harder to make out than others e.g Black.	34.721	0	34.16667	27.5	After performing the AR task first I found myself skipping reading which box to select bricks from. I kept looking up from the instructions and expecting to know where to take a brick from and having to look back at the instructions before continuing.
148	hmd	voice	text	26-40	m	Student	1	4	4ar/p	127.502	0	19.16667	27.5	The voice commands were not very responsive. Improving these would improve the usability of the system	40.902	0	5.833333	10	Paper instructions were simple and easy to follow.
149	hmd	voice	video	18-25	m	student	3	5	5ar/p	154.599	5	6.666667	17.5	ok	62.788	1	58.33333	40	a lot more effort required
145	hmd	native	text	41-65	f	PhD Student	1	3	3ar/p	279.571	1	50.83333	65	it was difficult initially to get the gestures right but I found it a lot easier at the end of the task. I couldn't see the whole of the screen most of the time I had to move the headset to find certain items this may be because of the broken headband!	49.424	0	30.83333	50	I found this easier than the VR one but I can imagine if you were using it for a more complex task or for longer it would get more difficult. the fact that you had to remember different letters in a non-alphabetic sequence would quickly make it become more demanding than the Vr option which

																			showed you which box to pick from
124	hmd	voice	text	26-40	m	PhD Candidate	3	5	4ar/p	225.996	0	22.5	40	The AR glasses can be difficult to mount on sometimes tricky to follow visual directions during the task steps.	46.658	0	20.83333	32.5	Using paper instructions can bring some uncertainty making me go back to the previous steps and making sure I completed them properly.
144	hmd	native	cad	26-40	f	PhD Student	1	2	3ar/p	165.773	1	9.166667	15	The initial alignment process proved a little tricky due to difficulty with the platform placement height. The red physical boxes with the Lego could sometimes make it more difficult to focus on the VR.	65.676	0	14.16667	30	No further comment.
202	mobile	native	cad	26-40	m	Research Associate	2	4	4p/ar	136.29	0	16.66667	30	Maybe the colour of the new piece could be a bit different so that it doesn't blend with the others.	90.024	0	16.66667	37.5	The contrast of some colours (e.g. red) is not very high - some more detail maybe needed
203	mobile	native	text	26-40	m	Research Assistant / PhD student	2	5	5p/ar	158.43	2	31.66667	77.5	n/a	38.597	0	28.33333	57.5	n/a
204	mobile	voice	cad	18-25	m	EngD Student	1	4	4p/ar	189.563	0	45	47.5	Voice control was less than ideal which is a little frustrating - when a task is complete I'd prefer not to have to shout at a phone to continue the task. Being able to interact more in 3D space with the instructions for placing was valuable as it made the placing easier to think about - and easier to understand.	39.251	0	39.16667	37.5	Finding orientation of blocks is difficult and requires majority of the concentration - it's unclear how each block has to be oriented in 3D space to fit
206	mobile	voice	text	26-40	m	PhD Student	5	4	5p/ar	160.574	0	19.16667	20	N/A	42.137	0	5	15	N/A
214	mobile	native	cad	26-40	m	Researcher	1	3	4ar/p	175.204	1	50.83333	37.5	there is no validation of each of the step during the process so in case of failure to the end product user will have no indication in which step he was wrong	63.256	2	32.5	30	having step 1 step 2 etc would help me identify to which step i was before
215	mobile	native	text	26-40	m	PhD Researcher	2	5	5ar/p	220.364	2	25	20	lll	53.404	0	21.66667	7.5	ll

205	mobile	native	video	26-40	f	PG Researcher	2	3	4p/ar	73.337	0	5	25	Straightforward and easy to use	68.917	2	10	17.5	.
217	mobile	voice	cad	18-25	m	Student & Bartender	1	4	3ar/p	172.335	0	22.5	30	it was useful but the voice activation was a little finicky	86.752	1	31.66667	22.5	n/a
218	mobile	voice	text	41-65	m	Consultant	1	4	5ar/p	142.229	0	24.16667	40	I found it unclear when I had jumped 2 steps (saying next twice because I didn't think the system had responded)	36.611	1	24.16667	35	I misplaced the first block and had to fix it.
207	mobile	voice	video	26-40	m	Eng D student	1	4	4p/ar	159.228	0	22.5	15	\	52.198	0	29.16667	15	\
216	mobile	native	video	26-40	m	Research assocciate	1	5	5ar/p	130.651	0	15.83333	12.5	none	40.529	0	10	22.5	none
219	mobile	voice	video	18-25	m	PhD Student	2	4	4ar/p	194.618	0	8.333333	15	Audio recognition could use a little improvement	54.554	0	4.166667	25	the task was simple and fun
226	mobile	native	cad	26-40	f	PhD Student	1	3	4ar/p	158.827	0	59.16667	60	It should be better if I can use both hand not held the mobile phone	47.108	0	45	37.5	I can revise or step back when I make mistake
227	mobile	native	text	26-40	m	Research Student	2	4	5p/ar	251.744	3	49.16667	25	Because it shows how the block should look at each stage it helped me notice an error while I was building so I could easily see what I had differed from the instructions and could go back and fix it.	36.953	0	44.16667	27.5	It works okay; boxes could be lined up in order if the process is consistent.
228	mobile	native	video	26-40	m	Student	2	5	4p/ar	140.799	1	20	22.5	Made one error when placing the 2nd or 3rd brick. May have been the angle of the video and I may also have rushed placing the brick.	42.565	0	22.5	22.5	A single image of each step from one POV meant that some thought was necessary to understand the orientation of the part in relation to the other pieces.
229	mobile	voice	cad	26-40	m	Research Associate	1	2	3p/ar	194.95	1	30.83333	37.5	None	34.24	0	28.33333	15	None
230	mobile	voice	text	18-25	m	PhD Student (Year 2)	3	4	4p/ar	186.798	0	54.16667	42.5	Fun quite an interesting alternative to the previous paper instructions.	46.205	0	27.5	15	unusual to work with varying letters for each step eg. not abcd... but it worked well.
231	mobile	voice	video	26-40	m	Postgraduate Research Student	1	4	4p/ar	102.511	0	25	27.5	I like the idea. The use of AR could help with tasks.	43.68	0	20	17.5	N/A
232	mobile	native	cad	26-40	m	PhD Student	3	5	5ar/p	78.487	0	21.66667	17.5	NA	45.042	0	21.66667	12.5	Felt more pressured with the digital task. Felt more confident

																			with the 3D aspect of the digital system.
233	mobile	native	text	18-25	m	Mechanical Engineering Student	3	4	4ar/p	95.999	0	7.5	27.5	Integration of being able to physically look around the model for different views of the instructions was useful	37.665	0	6.666667	32.5	It felt more familiar to me to use the paper instruction but the locked perspective caused a moment of confusion in where to place the next block
234	mobile	native	video	18-25	m	Undergraduate Student	2	4	4ar/p	118.504	1	32.5	37.5	The AR tracking was sometimes jumping around but this didn't affect being able to understand the instructions badly but it would help if it was improved.	57.249	0	34.16667	20	The cube was easier to build with the AR instructions as I could see how the pieces were intended to be fit together while with paper instructions I had to work out from the images how the pieces needed to be oriented to fit into place. The paper was however quicker as I didn't need to wait for the AR system to recognise tags in order to give me instructions.
235	mobile	voice	cad	26-40	m	PhD Student	2	4	5ar/p	207.813	0	14.16667	25	I think an augmented head set might improve the system rather than just a phone	49.028	0	25.83333	22.5	Well i have been building extremely complex Lego models since I was 6 hence this is extremely familiar territory to me.
236	mobile	voice	text	18-25	f	Full time student	2	4	5ar/p	194.448	1	41.66667	42.5		55.375	0	39.16667	32.5	
237	mobile	voice	video	26-40	f	PhD researcher	1	5	3ar/p	124.428	0	6.666667	27.5	None	108.503	1	5.833333	75	The first cube (D) is a bit tricky to see its direction

Appendix E. Study 4: Novelty and Learning

E.1 Sign Up Sheet and Participant Information

Introduction

You are invited to take part in a research study, exploring how Augmented Reality (AR) can be used for remote learning to allow users to learn new skills from their own homes. My name is Eleanor Smith, I am a PhD student in DMEM at the University of Strathclyde, and this study forms part of my PhD project, 'Industry 4.0 and Augmenting the Millennial Worker'.

There are two parts to this study, and you can choose to take part in either or both of them:

The first (**Study 1: AR Training**) uses a web based tool to guide the user through the task of measuring the voltage of a 3 phase power supply. We are looking for both complete novices and those with experience working with 3 phase power to take part in this study.

The second (**Study 2: Learning Curve**) guides users through a series of simple Lego assembly tasks (materials provided) to investigate whether performance improves with familiarisation, or decreases as the novelty effect wears off.

If you are interested in taking part of either or both of these studies, please proceed to the next page and fill in your details.

Privacy Notice
This is a sign up sheet for volunteers to take part in an experiment using Augmented Reality instruction manuals. If you would like to take part in this experiment, please enter your details below and indicate which (if any) studies you would like to take part in.

The personal data you provide here will be used to provide more information about participation in the studies, including a full Participant Information Sheet and Consent Form. The legal basis for processing your information under the 2018 Data Protection Act is consent. Your personal information will not be shared with any third parties. Your personal data will not be linked to your performance in the study. You are free to withdraw or cancel your participation at any time. Once the experiment is complete, all personal data (name, email) will be erased.

If you have any questions, please contact me at eleanor.smith@strath.ac.uk. For data protection queries, concerns or complaints you can contact dataprotection@strath.ac.uk or visit the University web page regarding information security.

Name First Name (optional)

____

Surname Surname (optional)

____

Email Email Address

____

Consent Consent

Please check the boxes below to confirm you have understood and agreed to your data being processed as explained in the Privacy Notice above.

- Yes (1)
- No (2)

End of Block: Intro/Priv/Consent

Start of Block: NoConsentGiven

NoConsent Without your consent, we cannot process your data to become a participant in this research. Thank you for your time.

End of Block: NoConsentGiven

Start of Block: Training?

Training? Would you like to take part in **Study 1: AR Training**?

This study uses a web based tool to guide the user through the task of measuring the voltage of a 3 phase power supply. We are looking for both complete novices and those with experience working with 3 phase power to take part in this study. You must be over 18 to take part.

To take part, you will need:
- Access to a printer (1 side of A4 in colour will need to be printed)
- Access to an internet connected smartphone
- You may take part regardless of your level of experience with 3 phase power or AR

- Yes (1)
- No (2)

End of Block: Training?

Start of Block: Learning?

Learning?
Would you like to take part in Study 2: Learning Curve?

A web based app will guide users through a series of simple Lego assembly tasks (materials provided) to investigate whether performance improves with familiarisation, or decreases as the novelty effect wears off. You must be over 18 to take part.

To take part, you will need:
- Access to an internet connected smartphone
- To be happy with receiving Lego bricks and a paper template through the post (UK addresses only please)
- You may take part regardless of your level of experience with Lego or AR

- Yes (1)
- No (2)

End of Block: Learning?

Start of Block: ConsentLearning

ConsentLearning **Consent FormName of department:** Design, Manufacturing and Engineering Management
Title of the study: Novelty and Learning Effects in Augmented Instructions
Please read the Participant Information Sheet here **and answer the questions below:**
Note: Unless you select all the options below, you will not be included in the study.

- I confirm that I have read and understood the Participant Information Sheet for the above project and the researcher has answered any queries to my satisfaction (1)
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences (2)
- I understand that anonymised data (i.e. data that do not identify me personally) cannot be withdrawn once they have been included in the study (3)
- I understand that any information recorded in the research will remain confidential and no information that identifies me will be made publicly available (4)
- I consent to being a participant in the project (5)

Address1 **Please provide a UK postal address to send the assembly kit.**

Address line 1:
____

Address2 Address line 2 (optional):

____

City City:

____

Postcode Postcode:

____

End of Block: ConsentLearning

Start of Block: Block 9

Q23 Background Questions
To help provide better context to my research data, I would appreciate if you could answer a few questions about who you are and what your background it. Like all the data collected throughout this process, it will be stored against a participant ID for anonymity. You do not have to answer these questions if you would prefer not to.

Q24 **Age group:**

- 18-25 years (1)
- 26-40 years (2)
- 41-65 years (3)
- 66 years and over (4)
- Prefer not to say (5)

Q25 **Gender:**

- Female (1)
- Male (2)
- Prefer not to say (4)
- Other (please specify) (5) ____

Q26 **What is your current occupation, job title, or role?**

____

Q27 **Please rate your abilities/experiences using the scale below**

	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	
Never used Augmented Reality	(	(	(	(	(	Expert user in Augmented Reality
Not at all comfortable with new and unfamiliar technologies	(	(	(	(	(	Extremely comfortable with new and unfamiliar technologies
No confidence in using IT and digital technology (e.g. PCs, smartphones, tablets)	(	(	(	(	(	Very confident in using IT and digital technology (e.g. PCs, smartphones, tablets)

End of Block: Block 9

Start of Block: Yto2

Yto2 Thank you for agreeing to participant in Study 2 (Learning Curve) - I will be in touch shortly to arrange everything. If you have any questions, please don't hesitate to get in touch with me at eleanor.smith@strath.ac.uk.
In the meantime, please consider sharing this with anyone else in your network who may be interested in taking part!

End of Block: Yto2

Start of Block: ConsentTraining

ConsentTraining **Consent FormName of department:** Design, Manufacturing and Engineering Management

Title of the study: Augmented Reality for Remote Training

Please read the Participant Information Sheet here **and answer the questions below:**

Note: Unless you select all the options below, you will not be included in the study.

- I confirm that I have read and understood the Participant Information Sheet for the above project and the researcher has answered any queries to my satisfaction (1)
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences (2)
- I understand that anonymised data (i.e. data that do not identify me personally) cannot be withdrawn once they have been included in the study (3)
- I understand that any information recorded in the research will remain confidential and no information that identifies me will be made publicly available (4)
- I consent to being a participant in the project (5)

3phase? Are you familiar with 3 phase power? i.e. confident in your ability to take a voltage reading using a multimeter

- Yes (6)
- No (7)

End of Block: ConsentTraining

Start of Block: Yto1

Yto1 Thank you for agreeing to participant in Study 1 (AR Training) - I will be in touch shortly to arrange everything. If you have any questions, please don't hesitate to get in touch with me at eleanor.smith@strath.ac.uk.
In the meantime, please consider sharing this with anyone else in your network who may be interested in taking part!

End of Block: Yto1

Start of Block: YtoBoth

YtoBoth Thank you for agreeing to participant in both studies - I will be in touch shortly to arrange everything. If you have any questions, please don't hesitate to get in touch with me at eleanor.smith@strath.ac.uk.
In the meantime, please consider sharing this with anyone else in your network who may be interested in taking part!

End of Block: YtoBoth

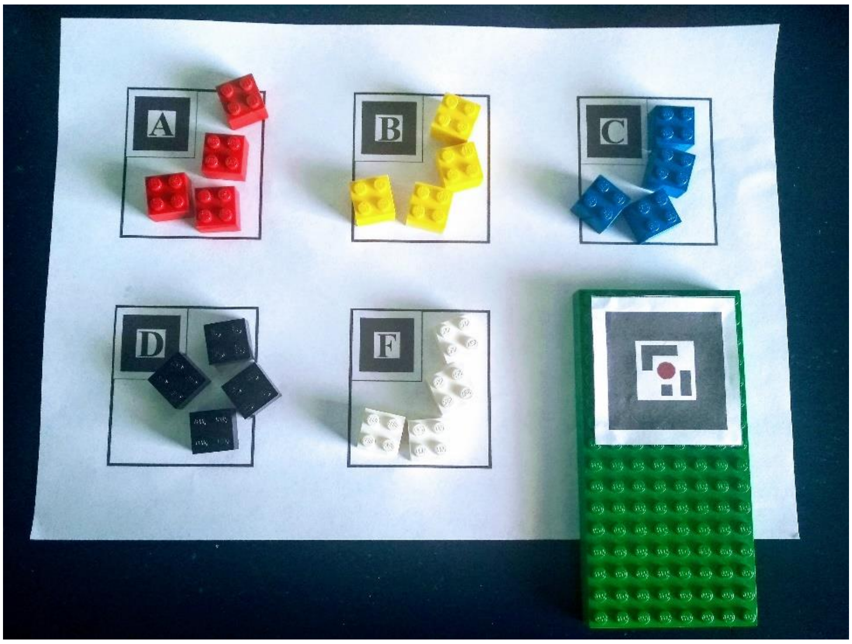
E.2 Email instructions

Hi <<Firstname>>,
Thank you for signing up to take part in my research study: Novelty and Learning Effects in Augmented Instructions.

When will I receive my kit?
Your Lego kit was sent by 1st class to the address below on <<Date>>:
<<Firstname>> <<Surname>>
<<Address>>
Please note that due to the ongoing coronavirus situation, there may be some postage delays. If you do not receive the kit within 10 days, please let me know and I will try and send out another one. Your kit should contain:

- 20 x Lego bricks (various colours)
- 1 x baseboard with marker attached
- 1 x layout sheet

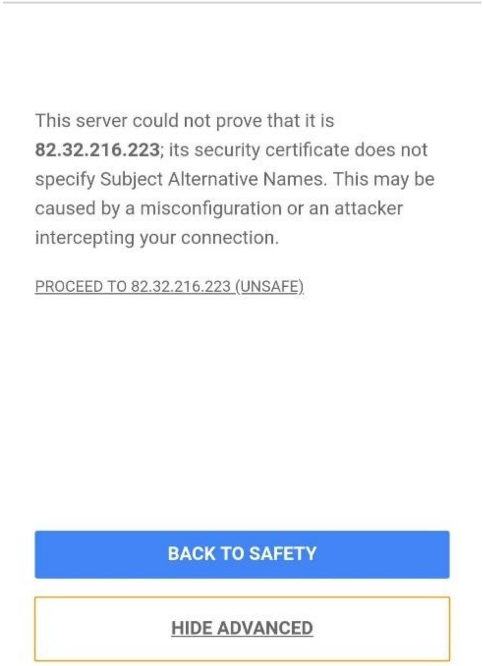
How do I get started?
Once you receive your kit, you can start the study. You'll need to lay out your kit on a flat surface, with the bricks in the corresponding blocks on the layout sheet, and the baseboard within easy reach, as below:

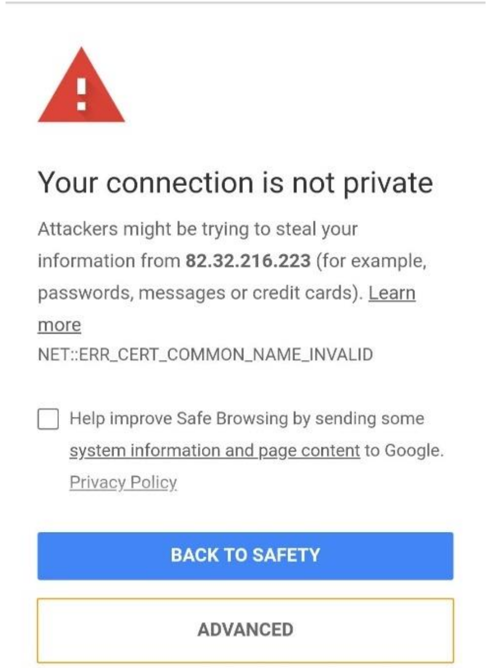


(TIP: MAKE SURE THE BLACK AND WHITE MARKERS ARE FULLY VISIBLE AT ALL TIMES, AND NOT OBSCURED BY BRICKS OR YOUR HANDS)
Once you've done this, you can begin the task by navigating to https://82.32.216.223:10000 on your mobile device. You'll need to return to this page each time you perform the task, so you may wish to bookmark this page. If you have a QR reader on your phone, you can scan the code below instead.

What do I need to do?

When you navigate to the webpage, you may see the screen below. If this is the case, please click 'Advanced' and 'Proceed to unsafe'

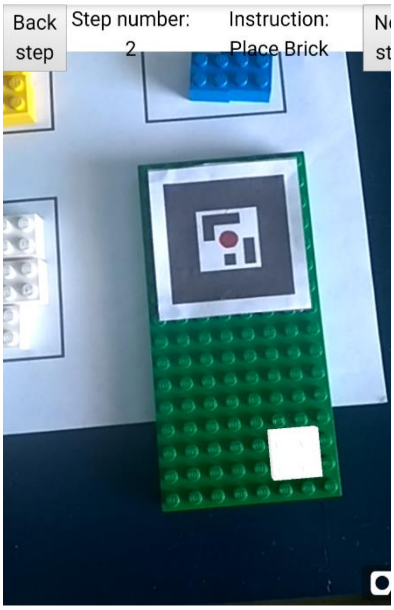




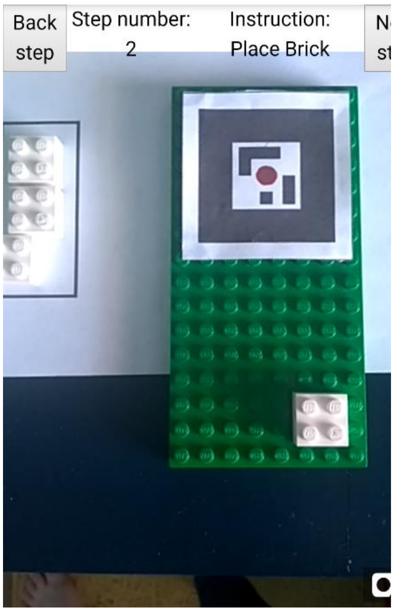
First, enter your participant ID, which is **<<PID>>**. Following the instructions on the webpage, you'll be guided through a simple assembly task – you'll need to accept any notifications asking you to 'allow access to camera'. The webpage uses the camera to look for black and white markers in your surroundings, and these tell it where to place virtual content. So on each 'pick' step, you'll need to move your camera over the layout sheet to look which colour brick to pick up. And on 'place' steps, you'll need to move your camera over the baseboard to see where to put the brick down again – remember to make sure the full marker is in view of the camera.

The diagrams below should help you understand what to do, but I have also recorded a video of myself carrying out the task, to give you a better idea. If you are struggling to get started, please get in touch and I'll see what I can do to help out.

EXAMPLE OF A 'PICK' STEP



EXAMPLE OF A 'PLACE' STEP



ACTUAL BRICK IN PLACE

How often do I need to do it?

I would like you to complete this task once a day for at least 5 days (you can keep going longer if you like) – every day the assembly will be slightly different, and your instructions will update accordingly.

What if I have questions?

If you have any questions, please do not hesitate to get in touch with me via return email, we can arrange a call if necessary, or check out this webpage for more information including instructional videos and participant information sheets.

Thank you so much for your help.

Kind regards,

Eleanor Smith
PhD Student
Advanced Forming Research Centre
Design, Manufacturing and Engineering Management
University of Strathclyde
Email: eleanor.smith@strath.ac.uk

Please consider sharing this with any of your friends and colleagues who may be interested to take part:

E.3 Full Results Table

Contained below is a table of only total time for the task, not individual times for each step.

PID	Date	Time	Total time	steps
411	04/08/2020	13:25:19	198.576	24
412	04/08/2020	14:18:04	186.1630001	22
413	04/08/2020	14:37:07	194.017	21
415	04/08/2020	15:23:25	187.3280001	20
430	04/08/2020	15:36:35	229.9630001	50
430	04/08/2020	15:41:28	146.8210001	22
413	05/08/2020	07:42:37	111.6589999	20
412	05/08/2020	08:22:43	248.1759999	20
415	05/08/2020	08:31:21	212.8269999	20
430	05/08/2020	09:19:15	191.263	30
419	05/08/2020	12:32:08	307.675	21
411	05/08/2020	14:52:21	195.0710001	21
412	06/08/2020	09:58:02	247.733	20
433	06/08/2020	12:03:12	151.2810001	20
413	06/08/2020	12:12:11	91.50900006	20
430	06/08/2020	16:47:38	127.9220002	22
411	06/08/2020	18:34:33	204.1830001	34
419	07/08/2020	08:22:21	178.1459999	20
430	07/08/2020	09:19:52	120.2589998	20
413	07/08/2020	12:34:12	94.73500013	20
406	07/08/2020	20:39:21	245.5309999	42
401	08/08/2020	01:25:14	110.214	23
413	08/08/2020	09:14:13	81.67400002	20
430	08/08/2020	11:14:00	154.4890001	22
429	08/08/2020	12:58:51	337.7419999	24
410	08/08/2020	20:07:14	396.345	20
463	08/08/2020	20:38:05	24.01600003	21
413	09/08/2020	09:41:47	86.27900004	20
429	09/08/2020	15:19:58	171.7179999	20
419	10/08/2020	08:16:17	146.9749999	20
429	10/08/2020	09:27:04	267.1639998	30
412	10/08/2020	10:51:53	98.76300001	20
418	10/08/2020	12:05:36	114.3299999	23
413	10/08/2020	12:26:56	75.30400014	20
422	10/08/2020	16:47:29	184.675	20
419	11/08/2020	08:11:35	119.8960001	20
418	11/08/2020	08:42:58	113.0699999	24
423	11/08/2020	09:08:29	193.2320001	20

433	11/08/2020	11:22:39	191.4630001	20
412	11/08/2020	13:29:32	116.0209999	22
429	11/08/2020	13:38:22	141.8049998	20
413	11/08/2020	14:07:20	172.247	20
422	11/08/2020	17:15:49	134.3110001	20
418	12/08/2020	07:09:10	107.5939999	24
413	12/08/2020	08:39:45	66.32500005	20
433	12/08/2020	08:55:02	134.266	20
419	12/08/2020	10:06:13	185.178	40
463	12/08/2020	14:37:26	213.1029999	22
463	12/08/2020	14:41:07	182.4650002	23
463	12/08/2020	14:47:19	107.852	20
422	12/08/2020	17:30:39	114.3869998	20
410	12/08/2020	20:47:03	236.1300001	20
433	13/08/2020	09:04:10	101.6209998	20
410	13/08/2020	12:22:39	117.609	20
410	13/08/2020	12:25:51	110.4689999	20
405	13/08/2020	12:28:50	185.8299999	21
405	13/08/2020	12:33:04	175.4719999	22
410	13/08/2020	12:37:32	113.6470001	21
410	13/08/2020	12:40:32	81.70700002	20
410	13/08/2020	12:42:24	125.724	20
418	13/08/2020	12:48:03	84.17700005	22
468	13/08/2020	14:48:31	371.7989998	20
422	13/08/2020	15:03:57	107.954	20
411	13/08/2020	19:51:47	181.273	20
468	14/08/2020	07:15:32	184.9520001	20
463	14/08/2020	08:13:38	152.2579999	20
409	14/08/2020	10:17:32	261.3460002	21
410	14/08/2020	12:00:44	125.628	20
405	14/08/2020	12:37:21	164.454	20
418	14/08/2020	15:34:28	72.91599989	22
422	14/08/2020	17:15:42	132.6789999	22
418	15/08/2020	09:11:02	98.30699992	20
463	15/08/2020	09:22:04	127.9260001	24
468	15/08/2020	11:01:22	179.6399999	22
429	15/08/2020	13:25:34	151.1259999	20
409	15/08/2020	15:11:35	219.987	20
422	15/08/2020	16:40:53	102.3510001	22
411	15/08/2020	19:59:09	155.066	20
468	16/08/2020	07:40:06	170.914	20
463	16/08/2020	10:22:38	150.6500001	20
429	16/08/2020	11:49:02	134.8099999	20
465	16/08/2020	13:19:18	953.1819999	26
465	16/08/2020	14:13:18	296.546	20
422	16/08/2020	17:43:57	120.474	20

405	16/08/2020	19:54:25	145.3050001	20
405	16/08/2020	19:58:05	112.4229999	20
410	16/08/2020	20:50:07	146.4980001	20
410	16/08/2020	21:36:33	121.0599999	20
463	17/08/2020	08:38:54	432.5450001	40
468	17/08/2020	11:18:36	204.4689999	20
422	17/08/2020	16:03:14	130.6859999	20
429	17/08/2020	19:02:57	158.4909999	20
410	17/08/2020	20:37:02	151.382	20
409	18/08/2020	00:10:28	257.125	20
463	18/08/2020	07:42:57	117.329	20
465	18/08/2020	08:31:58	141.723	20
416	18/08/2020	12:07:00	1167.347	29
422	18/08/2020	20:36:42	115.421	20
429	19/08/2020	08:16:35	128.329	20
463	19/08/2020	08:26:47	208.424	26
419	19/08/2020	13:01:32	129.2609999	21
465	19/08/2020	13:44:59	121.8440001	20
409	19/08/2020	14:35:11	275.4560001	20
416	19/08/2020	17:33:06	133.697	21
422	19/08/2020	18:58:25	106.4469998	20
465	20/08/2020	10:48:19	208.352	20
416	20/08/2020	12:45:29	183.704	20
422	20/08/2020	16:53:28	103.0040002	20
429	21/08/2020	09:02:02	141.744	20
465	21/08/2020	13:47:15	183.7850001	24
422	21/08/2020	18:25:21	111.823	20
417	22/08/2020	15:22:01	470.5770001	34
422	22/08/2020	21:16:09	107.5029998	28
422	23/08/2020	16:17:34	112.22	22
429	24/08/2020	08:26:32	133.1190002	20
422	24/08/2020	15:45:43	114.622	20
422	25/08/2020	16:23:31	111.378	20
409	25/08/2020	16:48:30	229.6470001	20
471	26/08/2020	12:22:21	141.6629999	20
409	26/08/2020	14:58:39	151.7820001	20
422	26/08/2020	15:28:34	99.0999999	20
405	26/08/2020	19:47:49	194.22	20
405	26/08/2020	19:52:57	253.5280001	22
471	27/08/2020	09:03:35	177.2920001	20
409	27/08/2020	10:05:39	224.75	20
474	27/08/2020	10:35:59	221.086	24
422	27/08/2020	16:20:58	107.6590002	20
478	27/08/2020	16:25:48	221.079	20
475	27/08/2020	18:39:40	181.3640001	20
475	27/08/2020	18:45:44	108.25	20

475	27/08/2020	18:48:05	87.26699996	20
480	28/08/2020	06:46:52	184.6420002	32
474	28/08/2020	10:27:11	118.8380001	20
471	28/08/2020	10:44:21	174.6029999	20
422	28/08/2020	16:58:14	92.48600006	20
478	28/08/2020	20:45:48	152.7089999	40
474	29/08/2020	09:15:17	91.30200005	40
478	30/08/2020	08:26:52	120.095	20
474	30/08/2020	10:02:24	99.76300001	22
471	30/08/2020	20:33:53	159.5350001	20
471	31/08/2020	08:50:40	116.6159999	20
474	31/08/2020	09:59:09	100.3940001	50
476	31/08/2020	20:29:38	198.993	30
474	01/09/2020	09:33:43	86.8440001	20
482	01/09/2020	11:42:17	330.825	24
478	01/09/2020	18:30:12	100.1289999	20
471	01/09/2020	20:38:17	125.7519999	22
474	02/09/2020	09:04:08	91.27699995	20
484	02/09/2020	11:31:06	197.4190001	21
471	02/09/2020	17:02:12	124.4659998	20
480	02/09/2020	20:01:12	170.1799998	20
474	03/09/2020	14:46:41	74.26800013	20
488	03/09/2020	19:54:03	178.4400001	20
473	03/09/2020	19:57:16	163.4469998	20
484	04/09/2020	08:49:12	106.733	20
474	04/09/2020	11:40:48	120.5509999	20
483	04/09/2020	13:27:00	157.204	20
488	04/09/2020	15:54:41	240.8860002	21
473	04/09/2020	18:44:35	174.7750001	24
478	04/09/2020	20:27:19	118.474	20
488	05/09/2020	09:38:59	109.5039999	20
486	05/09/2020	16:20:09	1049.281	68
478	05/09/2020	18:40:30	119.4589999	22
488	06/09/2020	09:10:14	116.9750001	20
484	06/09/2020	13:10:08	130.0839999	20
483	06/09/2020	16:27:19	187.582	20
486	07/09/2020	07:45:35	149.22	20
488	07/09/2020	08:23:40	120.5539999	20
477	07/09/2020	10:14:35	298.1129999	21
484	07/09/2020	15:50:35	91.66300011	20
473	07/09/2020	20:40:55	171.4220002	22
484	08/09/2020	08:00:12	96.91900015	20
486	08/09/2020	08:17:27	244.0279999	22
483	08/09/2020	10:50:29	197.8790002	22
482	08/09/2020	12:21:47	166.8900001	22
492	08/09/2020	17:15:55	146.786	20

473	08/09/2020	21:35:21	160.2809999	20
486	09/09/2020	09:41:14	244.3429999	32
492	09/09/2020	16:10:19	136.868	20
483	09/09/2020	16:22:33	95.59800005	20
415	09/09/2020	17:50:58	195.385	20
415	09/09/2020	18:03:39	2234.857	20
477	09/09/2020	21:44:51	134.3329999	20
486	10/09/2020	08:07:30	201.6860001	22
416	10/09/2020	10:42:14	154.086	20
416	10/09/2020	10:44:58	102.2550001	20
473	10/09/2020	12:55:03	114.194	20
492	10/09/2020	12:57:41	92.68999982	20
482	11/09/2020	11:31:27	91.69599986	20
423	11/09/2020	12:23:47	159.8770001	25
473	11/09/2020	16:06:29	139.5420001	22
483	11/09/2020	16:17:14	156.737	22
492	11/09/2020	21:10:32	167.095	24
479	12/09/2020	13:06:09	196.6059999	20
423	12/09/2020	13:42:29	99.25099993	20
403	12/09/2020	17:20:45	227.3069999	22
492	12/09/2020	18:07:12	118.5830002	20
473	12/09/2020	18:09:33	167.5139999	22
423	13/09/2020	17:29:46	240.0910001	39
483	13/09/2020	18:49:45	116.1509998	40
472	14/09/2020	11:17:19	260.96	21
479	14/09/2020	12:28:05	168.1530001	20
403	14/09/2020	21:01:35	169.0780001	22
403	14/09/2020	21:04:36	155.283	20
423	15/09/2020	08:50:38	119	20
472	15/09/2020	09:22:24	225.4070001	24
482	15/09/2020	09:52:40	112.6440001	20
403	15/09/2020	19:07:06	296.6460001	22
472	17/09/2020	16:15:38	139.8870001	21
472	19/09/2020	13:46:53	102.454	23
472	21/09/2020	17:13:29	111.3970001	23

Appendix F. Study 5: Engineering Education

F.1 Sign Up Sheet and Participant Information

As in E.1 – the same sign-up sheet was used to recruit for both studies.

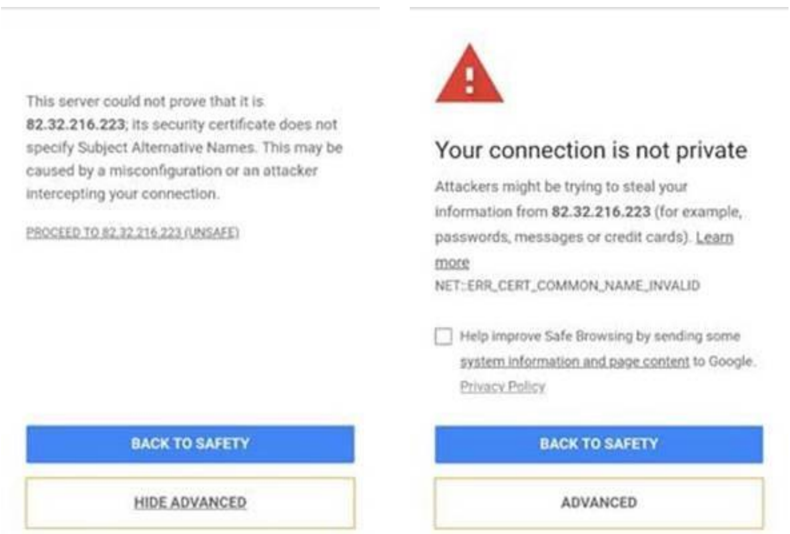
F.2 Email instructions

Hi <<Firstname>>,

Thank you for signing up to take part in my research study: Augmented Reality for Remote Training. You should access a PDF diagram of a 3 phase power system, annotated with black and white markers here – please print this off on A4 paper, ideally in colour. If you prefer, you can print out at A3 (or two A4s taped together) for a larger target. Your participant ID for this experiment is <<PID>>.
Although there is no time limit to this task and you should take as long as you need, we estimate this task typically takes under 45 minutes. Please aim to complete it by **Friday 18th September** if at all possible – please get in touch if you think you'll require longer than this.

How do I get started?
Once you've printed out your diagram, you can start the study. You can either lay you print out on a flat, well-lit surface, or you may find it easier to pin it up on a wall. Once you've done this, you can begin the task by navigating to <<URL>> on your mobile device (you'll need to return to this page each time you perform the task, so you may wish to bookmark this page). We recommend using **Chrome browser**.
Alternatively, you can scan the QR code below if you prefer:

When you navigate to the webpage, you may see the screen below. If this is the case, please click 'Advanced' and 'Proceed to unsafe'. Please also accept any pop-ups requesting permission to use your device camera.



The aim of the game is to diagnose faults on a simulated 3 phase power supply. You'll be presented with 4 scenarios, and guided through the process of making observations and taking voltage measurement. Based off this knowledge you will select one of the following conditions:

- No power
- Missing 1 or 2 phases
- Tripped MCCB
- Tripped overload
- Staying in star mode
- Broken delta contactor
- Broken motor
- No fault

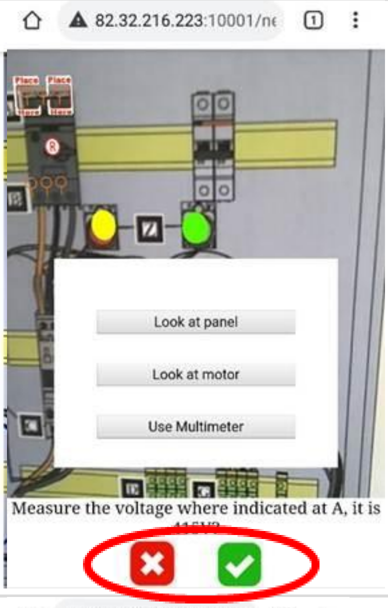
Included below is a brief overview of how the use and interact with the web app, you may also find it helpful to watch this video showing an example of how to use the app.

What do I need to do?

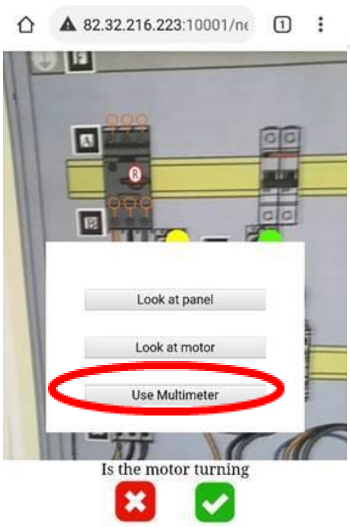
	• The first thing you will need to do is enter your **'Participant ID'**, which is **<<PID>>.** *NOTE: please type in your actual Participant ID, given above, not the example shown in the screenshot* • Point your phone at the printout (covered in letter markers) to reveal the extra AR content.
	• If the instruction at the bottom of the page reads 'Measure the voltage…' • From the Main Menu, select **'Use Multimeter'**.

	• Click and drag **the dial** around to the voltage setting. • Select the **'Place Probes'** button, and point your phone at the print out, making sure the letter specific in the instruction is in full view of the camera.
	• The **black circle in the centre of your screen** is the cursor, it represents the multimeter probe you are about to place. • You will also see 2 tags indicating the location at which you should place the probes (order is not important) • Select the first point you want to measure from by hovering the probe over that spot and tapping the screen to place the probe.

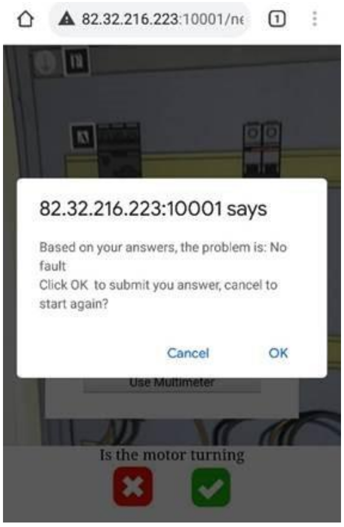
- You'll know you've placed it when the cursor flashes briefly white and then turns red
- The **red cursor** is your cue to place the **second probe**, using the same process.
- In the example shown here, we are taking a reading between the earth (at F) and point B



- Once you've placed both probes, you will be taken back to the multimeter, where you can see the reading taken.
- You may wish to make a note of this value.
- Click **'Return to Menu'**
- You can now answer the question on screen using the **tick and cross buttons**



- To check if the motor is running, select the **'Look at Motor'** option from the main menu
- You will see either an animation (if the motor is running) or a still image (if the motor is not running)



- When you’ve gathered enough information, you will be presented with a dialogue box suggesting what the fault may be.
- You can then either accept the suggestion, or cancel if you wish to re-take the measurements

Once you’ve finished, you’ll be directed to a link to a short questionnaire so you can provide me with feedback on your experience. You’ll need to enter your participant ID again here (<<PID>>).

What if I have questions?
If you have any questions, please do not hesitate to get in touch with me via return email, we can arrange a call if necessary, or check out this webpage for more information including instructional videos and participant information sheets.
Thank you so much for your help.

Kind regards,
Eleanor Smith
PhD Student
Advanced Forming Research Centre
Design, Manufacturing and Engineering Management
University of Strathclyde
Email: eleanor.smith@strath.ac.uk

F.3 Webpage containing Task Instructions

F.4 Post-Experiment Survey

AR for Remote Learning - Post Experiment Questionnaire (Expert Users)

Start of Block: Intro/PID

Introduction
Thank you for taking part in this experiment, your input will be very useful for my research! Now you've completed the task, I just have a few questions for you to answer about your experience and an opportunity for you to give feedback. Remember you can download a copy of the Participant Information, including information about how your data will be managed, from my webpage: http://personal.strath.ac.uk/eleanor.smith/.
If you wish to stay in touch, or here more about my research in future, do feel free to drop me an email at eleanor.smith@strath.ac.uk

Participant ID
You can find your participant ID in the email I sent you with the initial instructions for completing the task.

____

End of Block: Intro/PID

Start of Block: Block 2

Q28 **Mental Demand**

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How mentally demanding was the task? ()								

Q32 **Physical Demand**

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How physically demanding was the task? ()								

Q33 **Temporal Demand**

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How hurried or rushed was the pace of the task? ()								

Q34 **Performance**

	Perfect				Failure			
	0	3	6	9	12	15	18	21
How successful were you in accomplishing what you were asked to do? ()								

Q35 **Effort**

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How hard did you have to work to accomplish your level of performance? ()								

Q36 **Frustration**

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How insecure, discouraged, irritated, stressed, and annoyed were you? ()								

End of Block: Block 2
Start of Block: More Qs

Q39 Do you think you made any errors whilst completing the task?
(if yes, please elaborate)

- ◯ Yes (28)
- ◯ No (please specify) (29) ____

Q37 How similar was this AR training tool to the job of actually diagnosing faults on a 3 phase power supply?

	Very different (1)	Somewhat different (2)	Neither similar nor different (3)	Somewhat similar (4)	Very similar (5)
⊗How similar did you find this training task to the job of actually (1)	◯	◯	◯	◯	◯

Q41 The app which you used was aimed at 'expert users' who are already familiar with 3 phase electricity. Another version of the app has also been distributed to a group of 'novice users', which guides them through the process of fault diagnosis, step by step. The aim is then to compare performance between the two groups to discover if AR can be an effective teaching method in this case.

Would you be willing to try out the 'novice' training guidance application too, in order to provide feedback based on your experience working with this technology in real life? If yes, please use the box provided to enter an email address so I may get in touch.

○ Yes (1) ____

○ No (2)

Q38 Do you have any other feedback on how this work could be improved?

____

____

____

____

____

End of Block: More Qs

Start of Block: Thanks

Thank you

Thank you for your time and effort in contributing to this research. If you have any questions or feedback, please don't hesitate to get in touch with me at eleanor.smith@strath.ac.uk.

Please also consider sharing this with anyone else in your network who may be interested in taking part in either of my experiments!

End of Block: Thanks

F.5 Full Results Table

PID	Expert	Time	delta	1st measure	2nd measure	response	Submitted answer	Correct answer	% Correct	#Observat ions	Total time
501	Non-expert	11:24:15 18/09/2020		tpa2	tpa1	415			50%	10	00:03:26
		11:24:32 18/09/2020	00:00:17	tpb2	tpb1	0					
		11:24:51 18/09/2020	00:00:18				2	2			
		11:25:03 18/09/2020	00:00:12	tpa3	tpa1	415					
		11:25:16 18/09/2020	00:00:13	tpb2	tpb1	415					
		11:25:30 18/09/2020	00:00:14	tpc3	tpc1	415					
		11:25:43 18/09/2020	00:00:12	tpd3	tpd1	0					
		11:26:10 18/09/2020	00:00:27				3	3			
		11:26:22 18/09/2020	00:00:12	tpa2	tpa1	415					
		11:26:40 18/09/2020	00:00:18	tpb2	tpb1	415					
		11:26:54 18/09/2020	00:00:14	tpc2	tpc1	415					
		11:27:03 18/09/2020	00:00:10	tpd2	tpd1	415					
		11:27:14 18/09/2020	00:00:10				8	4			
		11:27:41 18/09/2020	00:00:28				5	1			
504	Non-expert	21:29:17 10/09/2020		tpb2	tpa1	230			75%	17	00:13:20
		21:29:35 10/09/2020	00:00:18	tpa1	tpa3	415					
		21:36:25 10/09/2020	00:06:50	tpb2	tpb1	0					
		21:36:33 10/09/2020	00:00:08	tpb3	tpb2	0					
		21:36:54 10/09/2020	00:00:21				2	2			
		21:37:33 10/09/2020	00:00:39	tpa3	tpa1	415					
		21:37:44 10/09/2020	00:00:11	tpa1	tpa3	415					
		21:38:07 10/09/2020	00:00:23	tpb1	tpb3	415					
		21:38:39 10/09/2020	00:00:32	tpc1	tpc2	415					

		21:38:59 10/09/2020	00:00:20	tpd1	tpb1	230					
		21:39:27 10/09/2020	00:00:28				3	3			
		21:39:58 10/09/2020	00:00:31	tpa2	tpa1	415					
		21:40:21 10/09/2020	00:00:22	tpb3	tpb2	415					
		21:40:35 10/09/2020	00:00:14	tpc2	tpc1	415					
		21:40:46 10/09/2020	00:00:11	tpc3	tpc1	415					
		21:41:08 10/09/2020	00:00:22	tpd2	tpd1	415					
		21:41:27 10/09/2020	00:00:19				8	4			
		21:41:47 10/09/2020	00:00:19	tpa2	tpa1	0					
		21:41:56 10/09/2020	00:00:10	tpa3	tpa2	0					
		21:42:22 10/09/2020	00:00:26	tpf1	tpa2	230					
		21:42:37 10/09/2020	00:00:14				1	1			
506	Non-expert	18:12:44 08/09/2020		tpb1	tpb2	0			40%	11	00:07:14
		18:13:12 08/09/2020	00:00:28	tpa2	tpa1	415					
		18:13:39 08/09/2020	00:00:27	tpb2	tpb1	0					
		18:14:09 08/09/2020	00:00:31	tpb2	tpb1	0					
		18:14:20 08/09/2020	00:00:11	tpb3	tpb1	0					
		18:14:35 08/09/2020	00:00:14				2	2			
		18:15:42 08/09/2020	00:01:08	tpb3	tpb2	415					
		18:16:08 08/09/2020	00:00:26	tpc3	tpc2	415					
		18:16:23 08/09/2020	00:00:15	tpd2	tpd1	0					
		18:16:37 08/09/2020	00:00:14	tpd2	tpd1	0					
		18:16:44 08/09/2020	00:00:07	tpd2	tpd1	0					
		18:16:57 08/09/2020	00:00:13	tpd2	tpd1	0					
		18:17:14 08/09/2020	00:00:17				3	3			
		18:17:55 08/09/2020	00:00:41				5	4			
		18:19:41 08/09/2020	00:01:46				6	2			
		18:19:58 08/09/2020	00:00:17				6	3			
507		12:49:28 10/09/2020		tpa1	tpb3	230			60%	21	00:09:27

		12:52:25 10/09/2020	00:02:57	tpa2	tpb3	230					
		12:53:23 10/09/2020	00:00:58	tpf1	tpa1	230					
		12:53:35 10/09/2020	00:00:12				1	2			
		12:54:19 10/09/2020	00:00:44	tpa3	tpa1	415					
		12:54:42 10/09/2020	00:00:23	tpb2	tpb3	0					
		12:54:51 10/09/2020	00:00:09	tpb3	tpb1	0					
		12:54:59 10/09/2020	00:00:08				2	2			
		12:55:34 10/09/2020	00:00:35	tpa3	tpa2	415					
		12:55:49 10/09/2020	00:00:15	tpb2	tpb1	415					
		12:55:54 10/09/2020	00:00:05	tpb3	tpb1	415					
		12:55:59 10/09/2020	00:00:05	tpb1	tpb2	415					
		12:56:14 10/09/2020	00:00:15	tpc3	tpc2	415					
		12:56:36 10/09/2020	00:00:21	tpd3	tpd1	0					
		12:56:38 10/09/2020	00:00:03	tpd3	tpd2	0					
		12:56:41 10/09/2020	00:00:03	tpd3	tpd2	0					
		12:56:58 10/09/2020	00:00:17				3	3			
		12:57:21 10/09/2020	00:00:23	tpa2	tpa1	415					
		12:57:32 10/09/2020	00:00:12	tpb3	tpb1	415					
		12:57:44 10/09/2020	00:00:12	tpc2	tpc1	415					
		12:57:56 10/09/2020	00:00:12	tpd2	tpd1	415					
		12:58:07 10/09/2020	00:00:11				8	4			
		12:58:24 10/09/2020	00:00:17	tpa2	tpa1	0					
		12:58:31 10/09/2020	00:00:07	tpa1	tpa3	0					
	Non-expert	12:58:50 10/09/2020	00:00:19	tpf1	tpa1	230					
		12:58:55 10/09/2020	00:00:05				1	1			
508	Non-expert	15:07:09 14/09/2020		tpa2	tpa1	415			75%	35	00:07:41
		15:07:45 14/09/2020	00:00:36	tpb2	tpb1	0					
		15:07:57 14/09/2020	00:00:12				2	2			
		15:08:21 14/09/2020	00:00:25	tpa3	tpa1	415					

15:08:39 14/09/2020	00:00:17	tpb2	tpb1	415		
15:08:59 14/09/2020	00:00:20	tpc2	tpc1	415		
15:09:05 14/09/2020	00:00:06	tpc2	tpc1	415		
15:09:10 14/09/2020	00:00:05	tpc2	tpc1	415		
15:09:23 14/09/2020	00:00:13	tpc1	tpc3	415		
15:09:40 14/09/2020	00:00:17	tpd2	tpd1	0		
15:09:44 14/09/2020	00:00:05	tpd3	tpd2	0		
15:09:58 14/09/2020	00:00:13	tpd3	tpd1	0		
15:10:04 14/09/2020	00:00:07	tpd2	tpd1	0		
15:10:15 14/09/2020	00:00:11	tpd2	tpd1	0		
15:10:22 14/09/2020	00:00:07	tpd2	tpd1	0		
15:10:29 14/09/2020	00:00:07	tpd2	tpd1	0		
15:10:32 14/09/2020	00:00:03	tpd2	tpd1	0		
15:10:40 14/09/2020	00:00:08	tpd2	tpd1	0		
15:10:57 14/09/2020	00:00:17	tpd2	tpd1	0		
15:11:02 14/09/2020	00:00:05	tpd1	tpd3	0		
15:11:06 14/09/2020	00:00:03	tpd2	tpd1	0		
15:11:15 14/09/2020	00:00:10	tpd2	tpd1	0		
15:11:23 14/09/2020	00:00:08	tpd2	tpd1	0		
15:11:29 14/09/2020	00:00:06	tpd1	tpd3	0		
15:11:42 14/09/2020	00:00:13	tpd2	tpd1	0		
15:11:53 14/09/2020	00:00:11	tpd3	tpd1	0		
15:11:59 14/09/2020	00:00:07	tpd2	tpd1	0		
15:12:06 14/09/2020	00:00:06	tpd3	tpd2	0		
15:12:08 14/09/2020	00:00:03	tpd2	tpd1	0		
15:12:19 14/09/2020	00:00:10	tpd2	tpd1	0		
15:12:36 14/09/2020	00:00:17				3	3
15:12:53 14/09/2020	00:00:17	tpa2	tpa1	415		
15:13:19 14/09/2020	00:00:27	tpb3	tpb1	415		
15:13:31 14/09/2020	00:00:12	tpc3	tpc1	415		

		15:13:44 14/09/2020	00:00:13	tpd3	tpd1	415					
		15:13:57 14/09/2020	00:00:13				8	4			
		15:14:15 14/09/2020	00:00:18	tpa2	tpa1	0					
		15:14:38 14/09/2020	00:00:23	tpf1	tpa1	230					
		15:14:50 14/09/2020	00:00:11				1	1			
516	Non-expert	10:28:36 25/09/2020		tpa1	tpa2	415			75%	12	00:06:19
		10:29:03 25/09/2020	00:00:27	tpb1	tpb3	0					
		10:29:17 25/09/2020	00:00:14				2	2			
		10:29:51 25/09/2020	00:00:34	tpa1	tpa3	415					
		10:30:11 25/09/2020	00:00:19	tpb1	tpb3	415					
		10:30:41 25/09/2020	00:00:30	tpc1	tpc3	415					
		10:30:59 25/09/2020	00:00:18	tpd2	tpd1	0					
		10:31:31 25/09/2020	00:00:32				3	3			
		10:31:57 25/09/2020	00:00:26	tpa1	tpa3	415					
		10:32:27 25/09/2020	00:00:30	tpb3	tpb2	415					
		10:32:52 25/09/2020	00:00:25	tpc1	tpc2	415					
		10:33:15 25/09/2020	00:00:23	tpd2	tpd1	415					
		10:33:34 25/09/2020	00:00:19				8	4			
		10:34:00 25/09/2020	00:00:26	tpa2	tpa1	0					
		10:34:46 25/09/2020	00:00:46	tpf1	tpa1	230					
		10:34:55 25/09/2020	00:00:09				1	1			
517	Non-expert	16:32:52 18/09/2020		tpb2	tpa3	230			67%	11	00:12:01
		16:33:35 18/09/2020	00:00:43	tpd2	tpd1	0					
		16:34:31 18/09/2020	00:00:55	tpb2	tpa1	230					
		16:35:20 18/09/2020	00:00:49				8	2			
		16:37:06 18/09/2020	00:01:46	tpc1	tpa3	415					
		16:38:51 18/09/2020	00:01:45				2	2			
		16:41:29 18/09/2020	00:02:38	tpa3	tpa2	415					
		16:41:39 18/09/2020	00:00:10	tpa1	tpa3	415					

		16:42:04 18/09/2020	00:00:26	tpb2	tpb3	415					
		16:42:24 18/09/2020	00:00:20	tpc2	tpc1	415					
		16:42:40 18/09/2020	00:00:17	tpd3	tpd2	0					
		16:42:57 18/09/2020	00:00:16	tpd1	tpd2	0					
		16:44:15 18/09/2020	00:01:18	tpd2	tpd3	0					
		16:44:53 18/09/2020	00:00:38				3	3			
521	Non-expert	09:59:25 15/09/2020		tpb2	tpb1	0			67%	44	00:11:10
		09:59:42 15/09/2020	00:00:17	tpa2	tpa1	415					
		09:59:57 15/09/2020	00:00:16	tpa3	tpa2	415					
		10:00:02 15/09/2020	00:00:05	tpa2	tpa1	415					
		10:00:24 15/09/2020	00:00:22	tpa2	tpa1	415					
		10:00:31 15/09/2020	00:00:07	tpa2	tpa1	415					
		10:01:19 15/09/2020	00:00:48	tpa3	tpa1	415					
		10:01:35 15/09/2020	00:00:16	tpb3	tpb2	0					
		10:01:42 15/09/2020	00:00:07	tpb3	tpb1	0					
		10:01:52 15/09/2020	00:00:10	tpb2	tpb1	0					
		10:02:27 15/09/2020	00:00:35	tpa1	tpa2	415					
		10:02:49 15/09/2020	00:00:22	tpb2	tpb1	0					
		10:03:09 15/09/2020	00:00:19	tpb1	tpb3	0					
		10:03:14 15/09/2020	00:00:05				2	2			
		10:03:31 15/09/2020	00:00:18	tpa2	tpa1	415					
		10:03:40 15/09/2020	00:00:09	tpa2	tpa3	415					
		10:03:48 15/09/2020	00:00:08	tpb3	tpa2	415					
		10:03:52 15/09/2020	00:00:04	tpb1	tpb2	415					
		10:04:01 15/09/2020	00:00:09	tpc2	tpc1	415					
		10:04:05 15/09/2020	00:00:04	tpc3	tpc1	415					
		10:04:10 15/09/2020	00:00:05	tpd2	tpd1	0					
		10:04:21 15/09/2020	00:00:11	tpd3	tpd1	0					
		10:04:29 15/09/2020	00:00:08	tpd2	tpd3	0					

		10:05:26 15/09/2020	00:00:57	tpd3	tpa3	230					
		10:05:38 15/09/2020	00:00:12	tpd3	tpa1	230					
		10:05:45 15/09/2020	00:00:06				1	2			
		10:06:03 15/09/2020	00:00:18	tpa2	tpa3	415					
		10:06:13 15/09/2020	00:00:11	tpb1	tpb2	415					
		10:06:22 15/09/2020	00:00:09	tpc1	tpc3	415					
		10:06:28 15/09/2020	00:00:05	tpd3	tpd2	0					
		10:06:31 15/09/2020	00:00:03	tpd2	tpd1	0					
		10:06:37 15/09/2020	00:00:06	tpd2	tpd1	0					
		10:08:22 15/09/2020	00:01:45	tpa2	tpa3	415					
		10:08:27 15/09/2020	00:00:05	tpb3	tpb2	0					
		10:08:30 15/09/2020	00:00:03	tpb2	tpb1	0					
		10:08:34 15/09/2020	00:00:03				2	2			
		10:08:45 15/09/2020	00:00:11	tpa1	tpa2	415					
		10:08:52 15/09/2020	00:00:07	tpb2	tpb3	415					
		10:08:57 15/09/2020	00:00:05	tpc3	tpc2	415					
		10:09:02 15/09/2020	00:00:05	tpd3	tpd2	0					
		10:09:06 15/09/2020	00:00:04				3	3			
		10:09:20 15/09/2020	00:00:13	tpa3	tpa2	415					
		10:09:24 15/09/2020	00:00:05	tpb3	tpb2	415					
		10:09:30 15/09/2020	00:00:05	tpc3	tpc2	415					
		10:09:35 15/09/2020	00:00:06	tpd2	tpd3	415					
		10:09:41 15/09/2020	00:00:06				8	4			
		10:10:07 15/09/2020	00:00:26	tpa1	tpa3	0					
		10:10:16 15/09/2020	00:00:09	tpa2	tpa1	0					
		10:10:31 15/09/2020	00:00:15	tpa1	tpf1	230					
		10:10:35 15/09/2020	00:00:05				1	1			
522	Non-expert	08:08:07 08/09/2020		tpa3	tpa1	415			0%	11	00:03:49
		08:08:32 08/09/2020	00:00:25	tpc2	tpc1	0					

		08:08:41 08/09/2020	00:00:10				6	2			
		08:09:12 08/09/2020	00:00:30	tpa3	tpa1	415					
		08:09:34 08/09/2020	00:00:22	tpb2	tpb1	415					
		08:09:56 08/09/2020	00:00:22	tpd2	tpd1	0					
		08:10:11 08/09/2020	00:00:15				4	3			
		08:10:29 08/09/2020	00:00:17	tpa2	tpa1	415					
		08:10:41 08/09/2020	00:00:12	tpb2	tpb1	415					
		08:10:52 08/09/2020	00:00:11	tpc3	tpc1	415					
		08:11:04 08/09/2020	00:00:12	tpd2	tpd1	415					
		08:11:15 08/09/2020	00:00:10				8	4			
		08:11:32 08/09/2020	00:00:18	tpa3	tpa1	0					
		08:11:48 08/09/2020	00:00:16	tpd1	tpa1	0					
		08:11:56 08/09/2020	00:00:08				5	1			
556	Expert	09:33:48 18/09/2020		tpb3	tpb1	0			50%	16	00:04:07
		09:34:02 18/09/2020	00:00:13				2	2			
		09:34:21 18/09/2020	00:00:19	tpa3	tpa1	415					
		09:34:36 18/09/2020	00:00:16	tpb3	tpb1	415					
		09:34:58 18/09/2020	00:00:22	tpc3	tpc1	415					
		09:35:13 18/09/2020	00:00:14	tpd2	tpd1	0					
		09:35:25 18/09/2020	00:00:13	tpd3	tpd1	0					
		09:35:36 18/09/2020	00:00:11				3	3			
		09:35:59 18/09/2020	00:00:23	tpa1	tpb3	415					
		09:36:05 18/09/2020	00:00:06	tpa3	tpa1	415					
		09:36:22 18/09/2020	00:00:17	tpb2	tpb1	415					
		09:36:33 18/09/2020	00:00:11	tpc2	tpc1	415					
		09:36:36 18/09/2020	00:00:03	tpc2	tpc1	415					
		09:36:40 18/09/2020	00:00:05	tpc2	tpc1	415					
		09:36:54 18/09/2020	00:00:13	tpd2	tpd1	415					
		09:37:03 18/09/2020	00:00:09				8	4			

		09:37:21 18/09/2020	00:00:18	tpa3	tpa1	0					
		09:37:29 18/09/2020	00:00:08	tpa2	tpa1	0					
		09:37:51 18/09/2020	00:00:22	tpb3	tpa1	0					
		09:37:56 18/09/2020	00:00:05				5	1			
558	Expert	21:31:08 20/09/2020		tpb1	tpa1	230			50%	9	00:06:28
		21:31:18 20/09/2020	00:00:10	tpb1	tpa2	230					
		21:31:27 20/09/2020	00:00:09	tpa2	tpb2	230					
		21:34:16 20/09/2020	00:02:49	tpc1	tpb1	0					
		21:34:51 20/09/2020	00:00:35	tpc1	tpf1	0					
		21:35:01 20/09/2020	00:00:10	tpf1	tpc1	0					
		21:35:29 20/09/2020	00:00:28	tpa1	tpf1	230					
		21:36:07 20/09/2020	00:00:38				2	2			
		21:36:27 20/09/2020	00:00:20			Motor started					
		21:36:37 20/09/2020	00:00:10	0	0	0					
		21:36:45 20/09/2020	00:00:08			MCCB Reset					
		21:37:01 20/09/2020	00:00:16			Motor started					
		21:37:11 20/09/2020	00:00:10	0	0	0					
		21:37:36 20/09/2020	00:00:25				4	3			
559	Expert	16:40:30 09/09/2020		tpb2	tpb1	0			0%	49	00:23:11
		16:45:40 09/09/2020	00:05:10			Motor wont start					
		16:45:50 09/09/2020	00:00:10	0	0	0					
		16:46:14 09/09/2020	00:00:24	tpc1	tpb2	0					
		16:46:32 09/09/2020	00:00:18	tpc2	tpc3	0					
		16:46:59 09/09/2020	00:00:27	tpf1	tpb2	0					
		16:47:44 09/09/2020	00:00:45			Motor wont start					
		16:47:54 09/09/2020	00:00:10	tpf1	tpb2	0					
		16:48:17 09/09/2020	00:00:22	tpf1	tpb2	0					
		16:48:53 09/09/2020	00:00:37	tpc3	tpc2	0					
		16:49:20 09/09/2020	00:00:26	tpf1	tpc2	0					

16:49:54 09/09/2020	00:00:34	tpg2	tpd2	0		
16:50:14 09/09/2020	00:00:20				5	2
16:50:49 09/09/2020	00:00:34	tpf1	tpb2	230		
16:51:02 09/09/2020	00:00:13			Motor started		
16:51:12 09/09/2020	00:00:10	tpf1	tpb2	230		
16:51:27 09/09/2020	00:00:15				8	3
16:52:02 09/09/2020	00:00:36	tpg2	tpd2	230		
16:52:10 09/09/2020	00:00:07	tpg2	tpc2	230		
16:52:28 09/09/2020	00:00:18	tpf1	tpg2	0		
16:54:22 09/09/2020	00:01:55	tpd2	tpd1	0		
16:54:30 09/09/2020	00:00:08	tpg2	tpd1	0		
16:56:00 09/09/2020	00:01:30			Motor started		
16:56:02 09/09/2020	00:00:02			Motor started		
16:56:10 09/09/2020	00:00:08	tpg2	tpd1	0		
16:56:12 09/09/2020	00:00:01	tpg2	tpd1	0		
16:56:31 09/09/2020	00:00:19	tpf1	tpa2	230		
16:56:40 09/09/2020	00:00:09	tpf1	tpa1	230		
16:56:49 09/09/2020	00:00:09	tpf1	tpa3	230		
16:56:55 09/09/2020	00:00:06	tpf1	tpb1	230		
16:57:01 09/09/2020	00:00:05	tpf1	tpb2	230		
16:57:08 09/09/2020	00:00:08	tpf1	tpb3	230		
16:57:17 09/09/2020	00:00:08	tpf1	tpc1	0		
16:57:28 09/09/2020	00:00:11	tpf1	tpc2	0		
16:57:37 09/09/2020	00:00:09	tpf1	tpc3	0		
16:57:45 09/09/2020	00:00:08	tpf1	tpb2	230		
16:57:51 09/09/2020	00:00:06	tpf1	tpb1	230		
16:58:24 09/09/2020	00:00:33	tpf1	tpg1	0		
16:58:32 09/09/2020	00:00:08	tpf1	tpd1	0		
16:58:38 09/09/2020	00:00:06	tpf1	tpd2	0		
16:58:41 09/09/2020	00:00:03	tpf1	tpd3	0		

		16:58:45 09/09/2020	00:00:04	tpg1		tpf1		0					
		16:58:48 09/09/2020	00:00:03	tpg2		tpf1		0					
		16:58:52 09/09/2020	00:00:04	tpg3		tpf1		0					
		16:59:33 09/09/2020	00:00:41	tpf1		tpg2		0					
		17:00:16 09/09/2020	00:00:44						6	4			
		17:00:35 09/09/2020	00:00:19					Motor started					
		17:00:45 09/09/2020	00:00:10		0		0	0					
		17:01:25 09/09/2020	00:00:40	tpf1		tpc2		0					
		17:01:36 09/09/2020	00:00:11	tpf1		tpc3		0					
		17:01:46 09/09/2020	00:00:10	tpf1		tpc1		0					
		17:01:52 09/09/2020	00:00:06	tpd1		tpc1		0					
		17:02:00 09/09/2020	00:00:08	tpc1		tpd2		0					
		17:02:07 09/09/2020	00:00:07	tpg1		tpc1		0					
		17:02:13 09/09/2020	00:00:06	tpf1		tpc1		0					
		17:02:26 09/09/2020	00:00:13	tpf1		tpb2		230					
		17:02:50 09/09/2020	00:00:23	tpf1		tpc3		0					
		17:03:00 09/09/2020	00:00:10	tpf1		tpc2		0					
		17:03:41 09/09/2020	00:00:41						2	1			
562	Expert	10:08:39 15/09/2020						Motor wont start			0%	13	00:14:33
		10:08:49 15/09/2020	00:00:10		0		0	0					
		10:10:05 15/09/2020	00:01:16	tpb2		tpf1		0					
		10:11:32 15/09/2020	00:01:27	tpb2		tpf1		0					
		10:12:28 15/09/2020	00:00:56	tpb3		tpf1		0					
		10:12:41 15/09/2020	00:00:13						5	2			
		10:14:12 15/09/2020	00:01:31	tpb2		tpf1		230					
		10:14:30 15/09/2020	00:00:18						8	3			
		10:15:19 15/09/2020	00:00:48						8	4			
		10:16:21 15/09/2020	00:01:02	tpd2		tpf1		0					
		10:16:39 15/09/2020	00:00:19	tpb2		tpf1		230					

		10:16:50 15/09/2020	00:00:11						8	1			
		10:19:16 15/09/2020	00:02:26					MCCB Reset					
		10:19:28 15/09/2020	00:00:12					Motor started					
		10:19:38 15/09/2020	00:00:10		0		0	0					
		10:19:44 15/09/2020	00:00:06						2	3			
		10:20:15 15/09/2020	00:00:30					Motor started					
		10:20:25 15/09/2020	00:00:10		0		0	0					
		10:21:19 15/09/2020	00:00:54					MCCB Reset					
		10:21:30 15/09/2020	00:00:11						2	4			
		10:21:51 15/09/2020	00:00:21					MCCB Reset					
		10:22:03 15/09/2020	00:00:12					Motor started					
		10:22:13 15/09/2020	00:00:10		0		0	0					
		10:22:35 15/09/2020	00:00:22	tpd1		tpf1		230					
		10:22:51 15/09/2020	00:00:16	tpb2		tpf1		230					
		10:23:07 15/09/2020	00:00:16	tpb3		tpf1		230					
		10:23:12 15/09/2020	00:00:05						8	1			
563	Expert	18:49:06 09/09/2020		tpg3		tpg2		0			0%	76	00:22:36
		18:49:15 09/09/2020	00:00:09	tpg1		tpg3		0					
		18:50:40 09/09/2020	00:01:25	tpg3		tpg2		0					
		18:51:13 09/09/2020	00:00:33					Motor wont start					
		18:51:23 09/09/2020	00:00:10	tpg3		tpg2		0					
		18:51:26 09/09/2020	00:00:04					Motor wont start					
		18:51:29 09/09/2020	00:00:02					Motor wont start					
		18:51:36 09/09/2020	00:00:08	tpg3		tpg2		0					
		18:51:39 09/09/2020	00:00:02	tpg3		tpg2		0					
		18:53:32 09/09/2020	00:01:53	tpb3		tpb2		0					
		18:54:36 09/09/2020	00:01:04					Motor wont start					
		18:54:47 09/09/2020	00:00:10		0		0	0					
		18:55:04 09/09/2020	00:00:18					Motor wont start					

18:55:14 09/09/2020	00:00:10	0	0	0
18:55:32 09/09/2020	00:00:18	tpg1	tpg2	0
18:56:03 09/09/2020	00:00:31	tpb3	tpb2	0
18:56:16 09/09/2020	00:00:13	tpg1	tpb3	0
18:56:23 09/09/2020	00:00:06	tpg1	tpb3	0
18:56:31 09/09/2020	00:00:08	tpg1	tpb3	0
18:56:34 09/09/2020	00:00:03	tpg1	tpb3	0
18:56:46 09/09/2020	00:00:12	tpg3	tpb3	0
18:56:50 09/09/2020	00:00:04	tpg3	tpb3	0
18:56:53 09/09/2020	00:00:04	tpg1	tpb3	0
18:56:58 09/09/2020	00:00:05	tpg2	tpb3	0
18:57:05 09/09/2020	00:00:06	tpg1	tpb3	0
18:57:11 09/09/2020	00:00:06	tpg3	tpb3	0
18:58:38 09/09/2020	00:01:27	tpg1	tpg2	0
18:58:41 09/09/2020	00:00:03	tpg2	tpg1	0
18:58:45 09/09/2020	00:00:03	tpg3	tpg2	0
18:59:00 09/09/2020	00:00:16	tpg3	tpg2	0
18:59:06 09/09/2020	00:00:05	tpg3	tpg2	0
18:59:22 09/09/2020	00:00:16	tpf1	tpg1	0
18:59:43 09/09/2020	00:00:21	tpc2	tpc1	0
19:00:04 09/09/2020	00:00:21	tpc2	tpc1	0
19:00:12 09/09/2020	00:00:08	tpc1	tpc3	0
19:00:27 09/09/2020	00:00:15	tpc3	tpc2	0
19:00:33 09/09/2020	00:00:06	tpc1	tpc3	0
19:00:36 09/09/2020	00:00:03	tpc2	tpc1	0
19:00:44 09/09/2020	00:00:08	tpb3	tpc1	0
19:00:48 09/09/2020	00:00:03	tpb2	tpb1	0
19:01:48 09/09/2020	00:01:00			Motor wont start
19:01:55 09/09/2020	00:00:07			Motor wont start
19:01:58 09/09/2020	00:00:03	0	0	0

19:02:05 09/09/2020	00:00:07	0	0	0
19:02:40 09/09/2020	00:00:35	tpc2	tpc1	0
19:02:52 09/09/2020	00:00:12	tpg1	tpc1	0
19:02:57 09/09/2020	00:00:05	tpg2	tpg1	0
19:03:03 09/09/2020	00:00:05	tpg1	tpg3	0
19:03:06 09/09/2020	00:00:03	tpd2	tpd3	0
19:03:10 09/09/2020	00:00:03	tpg1	tpd3	0
19:03:19 09/09/2020	00:00:09	tpb2	tpb3	0
19:03:21 09/09/2020	00:00:02	tpb2	tpb1	0
19:03:33 09/09/2020	00:00:12	tpb1	tpb2	0
19:03:36 09/09/2020	00:00:03	tpb1	tpb3	0
19:03:52 09/09/2020	00:00:16	tpb2	tpb3	0
19:04:03 09/09/2020	00:00:11	tpa2	tpa1	415
19:04:19 09/09/2020	00:00:15	tpa3	tpa2	415
19:04:28 09/09/2020	00:00:10	tpb2	tpb1	0
19:04:38 09/09/2020	00:00:10	tpb1	tpb3	0
19:04:40 09/09/2020	00:00:02	tpb2	tpb1	0
19:04:52 09/09/2020	00:00:12	tpf1	tpb3	0
19:05:04 09/09/2020	00:00:12	tpf1	tpb1	0
19:05:13 09/09/2020	00:00:09	tpc1	tpf1	0
19:05:24 09/09/2020	00:00:11	tpf1	tpc2	0
19:05:38 09/09/2020	00:00:14	tpc2	tpc1	0
19:05:42 09/09/2020	00:00:05	tpc2	tpc1	0
19:05:51 09/09/2020	00:00:08	tpd1	tpc3	0
19:06:10 09/09/2020	00:00:19	tpc2	tpd2	0
19:06:28 09/09/2020	00:00:18			MCCB Reset
19:06:33 09/09/2020	00:00:05			MCCB Reset
19:06:36 09/09/2020	00:00:03			MCCB Reset
19:06:40 09/09/2020	00:00:04			MCCB Reset
19:06:42 09/09/2020	00:00:02			MCCB Reset

19:06:45 09/09/2020	00:00:03			MCCB Reset		
19:06:51 09/09/2020	00:00:05			MCCB Reset		
19:06:55 09/09/2020	00:00:05			MCCB Reset		
19:07:02 09/09/2020	00:00:06			MCCB Reset		
19:07:04 09/09/2020	00:00:02			MCCB Reset		
19:07:07 09/09/2020	00:00:04			MCCB Reset		
19:07:14 09/09/2020	00:00:06			MCCB Reset		
19:07:21 09/09/2020	00:00:08			Motor started		
19:07:31 09/09/2020	00:00:10	tpc2	tpd2	0		
19:07:50 09/09/2020	00:00:18				6	2
19:08:04 09/09/2020	00:00:14			MCCB Reset		
19:08:09 09/09/2020	00:00:05			Motor started		
19:08:19 09/09/2020	00:00:10	0	0	0		
19:09:13 09/09/2020	00:00:54			MCCB Reset		
19:09:24 09/09/2020	00:00:11			Motor started		
19:09:34 09/09/2020	00:00:10	0	0	0		
19:09:51 09/09/2020	00:00:17	tpb1	tpb3	415		
19:10:04 09/09/2020	00:00:13	tpc1	tpb2	230		
19:10:07 09/09/2020	00:00:03	tpc2	tpc1	0		
19:10:11 09/09/2020	00:00:04	tpc1	tpc3	0		
19:10:14 09/09/2020	00:00:03	tpc3	tpc2	0		
19:10:19 09/09/2020	00:00:05	tpc1	tpc2	0		
19:10:27 09/09/2020	00:00:09	tpc1	tpc2	0		
19:10:33 09/09/2020	00:00:06	tpd2	tpd1	0		
19:10:36 09/09/2020	00:00:03	tpd3	tpd2	0		
19:10:40 09/09/2020	00:00:05	tpg2	tpg1	0		
19:11:02 09/09/2020	00:00:21			Motor wont start		
19:11:05 09/09/2020	00:00:03			MCCB Reset		
19:11:10 09/09/2020	00:00:05			Motor started		
19:11:12 09/09/2020	00:00:02	0	0	0		

		19:11:20 09/09/2020	00:00:08		0		0	0					
		19:11:29 09/09/2020	00:00:09					MCCB Reset					
		19:11:33 09/09/2020	00:00:04					Motor started					
		19:11:42 09/09/2020	00:00:09						6	2			
564	Expert	10:24:12 15/09/2020		tpb3		tpf1		0			0%	50	00:31:11
		10:24:47 15/09/2020	00:00:35	tpa1		tpb3		230					
		10:25:45 15/09/2020	00:00:58						7	2			
		10:27:28 15/09/2020	00:01:43					Motor wont start					
		10:27:38 15/09/2020	00:00:10		0		0	0					
		10:28:25 15/09/2020	00:00:48	tpa2		tpf1		230					
		10:28:52 15/09/2020	00:00:27	tpb2		tpb1		0					
		10:28:59 15/09/2020	00:00:07	tpb2		tpb1		0					
		10:29:52 15/09/2020	00:00:54	tpb1		tpf1		0					
		10:30:10 15/09/2020	00:00:17	tpf1		tpa1		230					
		10:30:26 15/09/2020	00:00:16	tpb2		tpf1		0					
		10:30:42 15/09/2020	00:00:16						1	2			
		10:31:29 15/09/2020	00:00:48					Motor started					
		10:31:39 15/09/2020	00:00:10		0		0	0					
		10:31:51 15/09/2020	00:00:11					Motor started					
		10:32:01 15/09/2020	00:00:10		0		0	0					
		10:32:48 15/09/2020	00:00:47	tpf1		tpa2		230					
		10:33:04 15/09/2020	00:00:16	tpf1		tpb1		230					
		10:33:14 15/09/2020	00:00:10	tpf1		tpa3		230					
		10:33:26 15/09/2020	00:00:12	tpb2		tpf1		230					
		10:33:49 15/09/2020	00:00:23	tpb2		tpf1		230					
		10:34:00 15/09/2020	00:00:11	tpb1		tpf1		230					
		10:34:28 15/09/2020	00:00:28	tpb1		tpc1		0					
		10:34:43 15/09/2020	00:00:15	tpc1		tpb2		415					
		10:34:54 15/09/2020	00:00:11	tpc3		tpb3		0					

10:35:07 15/09/2020	00:00:13	tpc1	tpf1	230		
10:35:17 15/09/2020	00:00:10	tpc2	tpf1	230		
10:35:26 15/09/2020	00:00:09	tpc3	tpf1	230		
10:35:44 15/09/2020	00:00:18	tpf1	tpd1	0		
10:35:54 15/09/2020	00:00:10	tpf1	tpg1	0		
10:36:12 15/09/2020	00:00:18	tpf1	tpd3	0		
10:36:26 15/09/2020	00:00:14	tpf1	tpg3	0		
10:36:39 15/09/2020	00:00:12	tpf1	tpg2	0		
10:37:01 15/09/2020	00:00:22				2	3
10:48:48 15/09/2020	00:11:47			Motor started		
10:48:52 15/09/2020	00:00:04			MCCB Reset		
10:48:58 15/09/2020	00:00:06	0	0	0		
10:49:46 15/09/2020	00:00:49	tpc1	tpf1	230		
10:49:59 15/09/2020	00:00:12	tpc2	tpf1	230		
10:50:07 15/09/2020	00:00:08	tpc3	tpf1	230		
10:50:21 15/09/2020	00:00:14	tpc3	tpf1	230		
10:50:40 15/09/2020	00:00:20	tpc3	tpb3	0		
10:50:45 15/09/2020	00:00:05	tpf1	tpd3	0		
10:51:02 15/09/2020	00:00:17	tpb2	tpf1	230		
10:51:10 15/09/2020	00:00:08	tpb3	tpf1	230		
10:51:19 15/09/2020	00:00:09	tpd1	tpb3	230		
10:51:34 15/09/2020	00:00:15	tpb3	tpf1	230		
10:51:38 15/09/2020	00:00:04	tpf1	tpb3	230		
10:51:43 15/09/2020	00:00:05	tpf1	tpb3	230		
10:51:47 15/09/2020	00:00:04	tpf1	tpb3	230		
10:52:12 15/09/2020	00:00:25	tpd1	tpf1	0		
10:52:33 15/09/2020	00:00:20	tpd2	tpf1	0		
10:52:39 15/09/2020	00:00:07	tpd2	tpd3	0		
10:52:48 15/09/2020	00:00:09	tpf1	tpg1	0		
10:53:04 15/09/2020	00:00:16	tpf1	tpg2	0		

		10:53:13 15/09/2020	00:00:09	tpf1	tpg3	0					
		10:53:35 15/09/2020	00:00:21	tpf1	tpb3	230					
		10:53:55 15/09/2020	00:00:21	tpg1	tpf1	0					
		10:54:19 15/09/2020	00:00:23				6	4			
		10:55:23 15/09/2020	00:01:04				4	1			
567	Expert	08:03:09 18/09/2020		tpa1	tpf1	230			67%	31	01:03:57
		08:03:21 18/09/2020	00:00:12	tpa2	tpf1	230					
		08:03:28 18/09/2020	00:00:07	tpf1	tpa3	230					
		08:03:38 18/09/2020	00:00:10	tpf1	tpa2	230					
		08:04:00 18/09/2020	00:00:22	tpa2	tpf1	230					
		08:04:11 18/09/2020	00:00:11	tpa3	tpf1	230					
		08:05:01 18/09/2020	00:00:50			Motor wont start					
		08:05:11 18/09/2020	00:00:10	0	0	0					
		08:05:29 18/09/2020	00:00:18	tpb1	tpf1	0					
		08:05:40 18/09/2020	00:00:11			MCCB Reset					
		08:05:49 18/09/2020	00:00:09			Motor started					
		08:05:53 18/09/2020	00:00:04				2	2			
		08:07:06 18/09/2020	00:01:14			Motor wont start					
		08:07:16 18/09/2020	00:00:10	0	0	0					
		08:07:35 18/09/2020	00:00:18	tpb1	tpf1	0					
		08:07:45 18/09/2020	00:00:10			MCCB Reset					
		08:07:52 18/09/2020	00:00:07			Motor started					
		08:08:01 18/09/2020	00:00:10				2	2			
		08:08:02 18/09/2020	00:00:00	tpb1	tpf1	230					
		08:54:21 18/09/2020	00:46:20			Motor wont start					
		08:54:31 18/09/2020	00:00:10	0	0	0					
		08:55:00 18/09/2020	00:00:28	tpb1	tpf1	0					
		08:55:07 18/09/2020	00:00:08			MCCB Reset					
		08:55:30 18/09/2020	00:00:23	tpb3	tpf1	230					

		08:55:48 18/09/2020	00:00:17	tpa1	tpf1	230					
		08:56:00 18/09/2020	00:00:12	tpc2	tpf1	0					
		08:56:09 18/09/2020	00:00:09	tpc3	tpc2	0					
		08:56:24 18/09/2020	00:00:15			Motor started					
		08:56:34 18/09/2020	00:00:10	tpc3	tpc2	415					
		08:56:52 18/09/2020	00:00:17				2	2			
		09:01:46 18/09/2020	00:04:54			Motor wont start					
		09:01:50 18/09/2020	00:00:04			MCCB Reset					
		09:01:55 18/09/2020	00:00:05			Motor started					
		09:01:56 18/09/2020	00:00:01	0	0	0					
		09:02:05 18/09/2020	00:00:09	0	0	0					
		09:02:50 18/09/2020	00:00:46	tpc1	tpf1	230					
		09:02:57 18/09/2020	00:00:07	tpc2	tpf1	230					
		09:03:05 18/09/2020	00:00:08	tpc3	tpf1	230					
		09:03:19 18/09/2020	00:00:14	tpg1	tpf1	0					
		09:03:33 18/09/2020	00:00:14	tpd1	tpf1	230					
		09:03:44 18/09/2020	00:00:11	tpd2	tpf1	230					
		09:03:53 18/09/2020	00:00:09	tpd2	tpf1	230					
		09:05:21 18/09/2020	00:01:28	tpd3	tpf1	230					
		09:05:21 18/09/2020	00:00:00	tpg1	tpf1	0					
		09:05:21 18/09/2020	00:00:00	tpg3	tpf1	0					
		09:05:30 18/09/2020	00:00:09				2	2			
		09:06:00 18/09/2020	00:00:29	tpc3	tpf1	0					
		09:06:26 18/09/2020	00:00:26				6	2			
		09:07:06 18/09/2020	00:00:40				8	2			
575	Non-expert	15:56:15 17/09/2020		tpa2	tpa1	415			50%	9	00:03:37
		15:56:49 17/09/2020	00:00:34	tpd1	tpb1	0					
		15:57:02 17/09/2020	00:00:14	tpf1	tpb1	0					
		15:57:15 17/09/2020	00:00:13	tpf1	tpb3	0					

		15:57:30 17/09/2020	00:00:15	tpf1	tpb3	0					
		15:57:49 17/09/2020	00:00:19				2	2			
		15:58:09 17/09/2020	00:00:20	tpf1	tpa1	230					
		15:58:33 17/09/2020	00:00:23				1	3			
		15:58:59 17/09/2020	00:00:26	tpa2	tpa1	415					
		15:59:09 17/09/2020	00:00:10	tpf1	tpa1	230					
		15:59:22 17/09/2020	00:00:13				1	4			
		15:59:43 17/09/2020	00:00:21	tpf1	tpa1	230					
		15:59:52 17/09/2020	00:00:09				1	1			
579	Non-expert	15:03:27 18/09/2020		tpa2	tpa1	415			75%	17	00:04:39
		15:03:51 18/09/2020	00:00:24	tpb3	tpb1	0					
		15:03:59 18/09/2020	00:00:08				2	2			
		15:04:30 18/09/2020	00:00:31	tpa3	tpa1	415					
		15:05:10 18/09/2020	00:00:40	tpb2	tpb1	415					
		15:05:23 18/09/2020	00:00:13	tpc2	tpc1	415					
		15:05:30 18/09/2020	00:00:07	tpc1	tpc3	415					
		15:05:39 18/09/2020	00:00:09	tpd2	tpd1	0					
		15:05:43 18/09/2020	00:00:05	tpd2	tpd1	0					
		15:05:48 18/09/2020	00:00:04	tpd3	tpd1	0					
		15:05:57 18/09/2020	00:00:10	tpd3	tpd2	0					
		15:06:16 18/09/2020	00:00:19				3	3			
		15:06:33 18/09/2020	00:00:17	tpa3	tpa1	415					
		15:06:43 18/09/2020	00:00:10	tpb2	tpb1	415					
		15:06:54 18/09/2020	00:00:11	tpc2	tpc1	415					
		15:07:01 18/09/2020	00:00:07	tpd2	tpd1	415					
		15:07:07 18/09/2020	00:00:06	tpd2	tpd1	415					
		15:07:16 18/09/2020	00:00:08				8	4			
		15:07:47 18/09/2020	00:00:31	tpa2	tpa1	0					
		15:07:59 18/09/2020	00:00:12	tpf1	tpa1	230					

		15:08:06 18/09/2020	00:00:07				1	1			
581	Expert	22:05:54 18/09/2020		tpa3	tpa1	415			75%	13	00:06:45
		22:06:13 18/09/2020	00:00:19	tpb3	tpb1	0					
		22:06:20 18/09/2020	00:00:07	tpb2	tpb1	0					
		22:07:03 18/09/2020	00:00:43				2	2			
		22:07:22 18/09/2020	00:00:19	tpa2	tpb1	415					
		22:07:35 18/09/2020	00:00:13	tpb2	tpb1	415					
		22:07:49 18/09/2020	00:00:15	tpc2	tpc1	415					
		22:08:13 18/09/2020	00:00:24	tpd3	tpd1	0					
		22:08:57 18/09/2020	00:00:44				3	3			
		22:09:18 18/09/2020	00:00:21	tpa2	tpa1	415					
		22:09:34 18/09/2020	00:00:16	tpb2	tpb1	415					
		22:09:51 18/09/2020	00:00:17	tpc2	tpc1	415					
		22:10:15 18/09/2020	00:00:24	tpb1	tpd1	0					
		22:10:59 18/09/2020	00:00:44				3	4			
		22:11:30 18/09/2020	00:00:31	tpa3	tpa1	0					
		22:12:03 18/09/2020	00:00:33	tpf1	tpa1	230					
		22:12:39 18/09/2020	00:00:36				1	1			

Appendix G. Study 6: Engineering Training

G.1 Coronavirus Risk Assessment

University of Strathclyde Glasgow

GENERAL RISK ASSESSMENT FORM (S20)

Persons who undertake risk assessments must have a level of competence commensurate with the significance of the risks they are assessing. It is the responsibility of each Head of Department or Director of Service to ensure that all staff are adequately trained in the techniques of risk assessment. The University document “Guidance on Carrying Out Risk Assessments” will be available, in due course, to remind assessors of the current practice used by the University. However, reading the aforementioned document will not be a substitute for suitable training.

Prior to the commencement of any work involving non-trivial hazards, a suitable and sufficient assessment of risks should be made and where necessary, effective measures taken to control those risks.

Individuals working under this risk assessment have a legal responsibility to ensure they follow the control measures stipulated to safeguard the health and safety of themselves and others.

SECTION 1

1.1 OPERATION / ACTIVITY	Complete the relevant details of the activity being assessed.		
Title:	Use of shared head worn AR device		
Department:	DMEM		
Location(s) of work:	Booth Welsh premises (partner company)	**Ref No.**	
Brief description: As part of PhD research to explore the use of Augmented Reality (AR) in manufacturing and maintenance, a user study is required to assess effectiveness of a proposed AR solution. This would require participants to be present on site with the researcher, and to wear an AR device on their head.			

1.2 PERSON RESPONSIBLE FOR MANAGING THIS WORK			
Name:	Andrew Britten	**Position:**	Control System Engineer
Signature:		**Date:**	
Department:	Booth Welsh		

1.3 PERSON CONDUCTING THIS ASSESSMENT

Name:	Eleanor Smith	**Signature:**	
Name:		**Signature:**	
Name:		**Signature:**	
Date risk assessment undertaken:	23/11/20		

1.4 ASSESSMENT REVIEW HISTORY

This assessment should be reviewed immediately if there is any reason to suppose that the original assessment is no longer valid. Otherwise, the assessment should be reviewed annually. The responsible person must ensure that this risk assessment remains valid.

	Review 1	**Review 2**	**Review 3**	**Review 4**
Due date:	May 2021			
Date conducted:				
Conducted by:				

Issued by Safety Services – Nov 2008 **Page of**

SECTION 2

Work Task Identification and Evaluation of Associated Risks				Page of	Ref No.				
Component Task / Situation	**Hazards Identified**	**Ha**	**Who Might be Harmed and How?**	**Existing Risk Control Measures (RCM)**	**Li ke**	**Se ve**	**Ri sk**	**Ri sk**	**R C**
Before attending site	Transmission of COVID-19 virus	1	Persons present on site during the work task	Those showing any symptoms of COVID-19 or other illness should not attend site and self-isolate per Government guidance Those sharing a household with anyone confirmed COVID-19 positive must not come onto site and must self-isolate Those notified by track and trace to self-isolate must do so and must not come onto site Only those considered fit to return to work under Booth Welsh's coronavirus risk assessment will be permitted to participate	3	5	15	H	Y
Contact with other people present on site (i.e. individuals from separate households)	Transmission of COVID-19 virus	2	Researcher or other people present on site may contract COVID-19 and fall ill	Maintain 2m physical distancing from other people at all times	3	5	15	H	Y
Co-location of researcher and participant (i.e. individuals from separate households)	Transmission of COVID-19 virus	3	Researcher or participant may contract COVID-19 and fall ill	Minimise time spent in same location by getting participants to fill out forms and surveys on their own devices in their own time Researcher and participant to wear face coverings Ensure good hand hygiene by use of hand sanitiser on entering and leaving the room Maintain 2m physical distancing between researcher and participant at all times –	3	5	15	H	Y

				use of a physical barrier (e.g. a desk) or floor markings to aid compliance					
Use of shared head worn equipment	Transmission of COVID-19 virus via shared surfaces	4	Researcher or participant may contract COVID-19 and fall ill	Only those considered fit to return to work under Booth Welsh's coronavirus risk assessment will be permitted to participate Devices to be sanitised using at least 70% alcohol wipes or aerosan surface sanitiser spray before and after each use – before by the participant, after by the researcher Devices to be quarantined for at least 72 hours between each use Devices not to be touched by the researcher (other than during sanitising), instructional videos used instead to help guide participant through the required process	3	5	15	H	Y
Use of researcher's laptop to fill in post-experiment questionnaire	Transmission of COVID-19 virus via shared surfaces	5	Researcher or participant may contract COVID-19 and fall ill	Only those considered fit to return to work under Booth Welsh's coronavirus risk assessment will be permitted to participate Link/QR code to questionnaire provided so participants can fill them in on their own devices	3	5	15	H	Y

SECTION 3

Identified Actions to Improve Control of Unacceptable Risks (as evaluated in Section 2)												Page of Ref No.
Hazard Ref No.	Risk	Recommended Additional Risk Control Measures	Implemented Y/N	Action By	Target Date	Completion Date	Revised Risk				Revision of Risk Signed Off
							Likelihood	Severity	Risk Rating	Risk L, M, H	

SECTION 4

RECORD OF SIGNIFICANT FINDINGS **Page of**

Ref No.

Where this Section is to be given to staff etc., without Sections 2 & 3, please attach to the front of this page, a copy of the relevant Section 1 details.

The significant findings of the risk assessment should include details of the following:

- The identified hazards
- Groups of persons who may be affected
- An evaluation of the risks
- The precautions that are in place (or should be taken) with comments on their effectiveness
- Identified actions to improve control of risks, where necessary

Alternatively, where the work activity/procedure is complex or hazardous, then a written Safe System of Work (SSOW) or Standard Operating Procedure (SOP) is advised that should incorporate the significant findings. Such documents should again, have the relevant Section 1 attached. Please state below whether either a SSOW or SOP is available in this case.

Relevant SSOW available	Yes ☐	No ☐	Relevant SOP available	Yes ☐	No ☐

Significant Findings: (Please use additional pages if further space is required)

- The identified hazards
  - Transmission of COVID-19 virus
- Groups of persons who may be affected
  - Anyone on present on site at the time of the experiment
- An evaluation of the risks
  - Coronavirus can cause serious harm in some individuals and can be fatal. Whilst the measures outlined below significantly reduce the risks, transmission is still possible.
- The precautions that are in place (or should be taken) with comments on their effectiveness
  - A 2m physical distance will be maintained from other people at all times – according to UK government advice, the risk of transmission is small at 2m physical distance[1]
  - Only those considered fit to return to work by Booth Welsh's coronavirus risk assessment will be on site and permitted to participate – this will reduce the likelihood of severe consequences if the virus was contracted
  - Time spent in the same location of the researcher will be minimised by any extraneous paperwork of surveys being carried out on the user's own devices in their own time – decreasing duration of contact, decreases the risk of transmission[1]
  - Both researcher and participant will wear face coverings – Scottish government consider face coverings to provide additional protection against transmission when used correctly[2]
  - Both researcher and participant will sanitise hands on entry and exit, shared devices will be sanitised before and after each use using alcohol wipes or spray, and quarantined for 72 hours between uses – UK government considers hand washing and high alcohol content sanitisers are an effective way of minimising transmission via surface contact[1]
  - The device will not be touched by anyone but the participant before use, except for the sanitising process – fewer contacts means reduced risk of transmission
- Identified actions to improve control of risks, where necessary

1 - https://www.gov.uk/government/publications/review-of-two-metre-social-distancing-guidance/review-of-two-metre-social-distancing-guidance

2 - https://www.gov.scot/publications/coronavirus-covid-19-public-use-of-face-coverings/#:~:text=The%20best%20available%20scientific%20evidence,metre%20distancing%20is%20not%20possible.&text=In%20such%20circumstances%20you%20are%20expected%20to%20wear%20a%20face%20covering.

SECTION 5

RECEIPT OF SIGNIFICANT FINDINGS OF RISK ASSESSMENT **Page of**

Please copy this page if further space is required. **Ref No.**

All individuals working to the risk assessment with the Ref. No. as shown, must sign and date this Section to acknowledge that they have read the relevant risk assessment and are aware of its contents, plus the measures taken (or to be taken by them) to safeguard their health and safety and that of others.

If following review of the assessment revisions are minor, signatories may initial these where they occur in the documentation, to indicate they are aware of the changes made. If revisions are major, it is advisable to produce a new risk assessment and signature page.

NAME (Print)	SIGNATURE	DATE

G.2 Safe System of Work

Safe System of Work for operation of Microsoft HoloLens

SSOW Number :	SSOW_
Machine Location:	Booth Welsh
Author(s):	Eleanor Smith
Reviewer(s):	
Date of Issue:	

General Information

This safe system of work summarises the instructions to be followed in order to carry out studies using Augmented Reality headsets in a safe manner, with particular regards to transmission of the COVID-19 virus. It is associated with the Risk Assessment, titled "Use of shared head worn AR device".

Safe Machine Operation

Participants should

- Complete any sign up sheets, consent forms, surveys etc beforehand in order to minimise time spent on site
- Wear a face covering at all times and maintain 2m physical distance from researcher
- Wash/sanitise hands on entry
- Use the 70% alcohol wipes provided to clean HoloLens before picking up and wearing
- Use a disposable mask pad to prevent direct contact with eye area
- Complete task as directed by researcher and instructional videos provided
- Wash/sanitise hands on exit
- Complete any post-experiment surveys on own device to minimise time spent on site

Researcher should:

- Wear a face covering at all times and maintain 2m physical distance from participant
- Wash/sanitise hands on entry
- Provide instructional videos and verbal guidance to users, using lie strema to monitor task progress, with no physical contact at any point
- Sanitise HoloLens with Aerosan biocide and virucide sanitising spray after use, place on charge and put on case along with coloured tags to track quarantine status
- Start timer on 72 hour quarantine period (device should not be touched again until quarantine period is complete)
- Wipe down surfaces and wash/sanitise hands on exit

Hazards

The main hazards associated with this work is the transmission of the COVID-19 virus, which transmits through both droplets and via shared surfaces. This SSoW outlines practises to reduce the risk of transmission via both of these modes, however a small risk remains and transmission is still possible.

Persons Reviewing SSOW	
Name:	**Signature:**
Name:	**Signature:**
Name:	**Signature:**

G.3 Booth Welsh COVID-19 Return to Work Policy

BOOTH WELSH
Integrated Engineering Services
a CLOUGH company

Management System

Covid-19 Return to Work Policy

REV	DATE	GENERAL DESCRIPTION	PREPARED	REVIEWED	ENDORSED
01	18/06/2020	Issued	AC	GM	MW

APPROVED	Martin Welsh
	Managing Director

	Approvals & Revision History				
Rev	Rev Description	Prepared	Reviewed	Endorsed	Date
00	Draft	AC			12/06/2020
01	Issued	AC	GM	MW	18/06/2020

Covid-19 Return to Work Policy

The health and safety of our employees and their families is our number one priority. We need everyone's help in returning to work safely and maintaining good health and wellbeing. Part of this process is ensuring that we don't have anyone working in the office if they become sick or display known symptoms of coronavirus Covid-19.
The following steps are critical to maintain a safe workplace for all employees. If you have any questions, please contact your line manager or the QEHS Manager.

1. **Prior to returning to any Booth Welsh workplace location**
   All employees should have received and completed the Covid-19 Risk Assessment for Return to Work which the HR department will use to determine your suitability to return to your normal place of work, and any additional measures that may be needed specific to your individual requirements such as:
   - If you are in a high risk category for Covid-19
   - If you have home/personal caring responsibilities
   - Work flexibility - discuss and agree with your line manager if you have concerns around returning to your normal place of work and what blended working options are available to you

   All employees must also complete a self—assessment of their current health condition using 'BWA-HSE-FO-G-0017 Covid-19 Screening Form' either immediately upon arrival or by submitting it electronically the day before their scheduled return date.
   - The reception area at head office will maintain a list of employees that have completed the COVID-19 Screening Self-Assessment Form.
   - Employees will be asked to leave the office if they fail to complete the COVID-19 Screening Form.
   - You will be required to have a temperature check before entry to the building. If you exhibit a temperature of 37.8° or above you must return home and seek professional medical advice.

2. **Do not come to work if you are unwell or have symptoms of coronavirus**
   - Symptoms include a new and continuous dry cough, shortness of breath, a temperature above 37.8°C or a loss or change to your sense of taste or smell.
   - If you begin to feel unwell or become sick during the shift or working day, inform your supervisor or line manager, leave and go home immediately, and seek professional medical advice.

3. Workplace Preparation

In preparation for returning to work, measures have been implemented to ensure your safety in line with advice available to us. Similar measures should or will have already been applied at other work locations e.g. client sites. In these cases adherence to the client's site requirements is to be followed.

The measures documented below are specific to head office:

- A one-way system has been implemented at head office; this is to be strictly adhered to.
- All areas of the building have been risk assessed for maximum occupancy and to ensure hygiene and distancing measures are adequate – results are posted at the entrance to each area to avoid ambiguity. Please adhere to all restrictions where they exist.
- Physical distancing – workstations have been assessed for compliance with physical distancing guidelines and their locations may have been moved or adjusted to achieve this.
- Common areas such as meeting rooms and kitchens have been adapted to minimize interactions and maintain distancing requirements. Physical screening has been installed where required e.g. Café Zero.
- Automatic opening doors and magnetic door holders have been installed to reduce contact points.
- Cleaning – cleaning of office space with additional of 'contact point' cleaning.
- A touch free hand sanitising station has been installed at the entrance to reception.
- Other hygiene measures – hand sanitizer, cleaning supplies, anti-bacterial wipes and face coverings are available to all employees.

4. Returning to Work – Borrowed IT Equipment and accessories

- Computers, monitors, and other peripherals and accessories that you borrowed while working from home should be brought back upon your permanent return to the office as there will be limited additional IT equipment available for use.
- If you need help connecting or setting up your IT equipment, contact the IT department.

5. Returning to Work – Workplace & Personal HSE Hazards

When re-entering the office and setting up equipment, remember the presence of common hazards:

- Electrical hazards – check cables and wiring is safe before switching equipment on.
- Manual handling – seek assistance if needed when manual handling.
- Ergonomics – when setting up or re-instating your workstation, check the setup of your desk, computer, screens, and chair in line with HSE Display Screen Equipment guidelines.
- Slip, trip and fall hazards – check for trailing cables, remove any packaging, clean up any spills which may occur.

6. **Returning to Work – Personal Travel Arrangements**

   Travel arrangements to and from work need to be considered:
   - Where possible use your own vehicle to get to and from work.
   - Cycling and walking are strongly encouraged as an alternative, where possible.
   - Car sharing is strongly discouraged, however where possible physical distancing can be achieved by carrying a passenger in the rear seat on the opposite side of the vehicle to the driver. In these circumstances face coverings should be worn, the windows opened and the air supply fan set to fresh (not recirculate) to allow fresh air to circulate in the vehicle.
   - The use of public transport should be avoided where possible, however where this can't be achieved, a face covering or mask is a government mandated requirement.

7. **Daily (Head Office) Procedures:**

   These steps may differ at your specific work location, specifically at client sites where their procedures should take precedence, however most will still apply and should be adhered to as much as possible, where practicable:
   - **In the event of an emergency**
     - In an emergency situation that requires evacuation of the building e.g. a fire, the first act must always be to vacate the building by the quickest route. Physical distancing is a secondary consideration during evacuation, however once the muster point is reached it must be adhered to again.
   - **Upon arrival each day**
     - Swipe in to gain access through the touch free doors. If you have forgotten your card, reception can open the doors for you without your need to touch them.

    - Record a temperature check – anyone with a temperature above 37.8°C will be asked to leave and seek professional medical advice.
- **After signing in**
    - Following the one way system, go directly to your office, workstation, or meeting location.
    - Only touch the points or enter areas required to get to your office, workstation, or meeting location.
    - Limit your movement within the workplace to the minimum required.
- **Maintain a Clean & Hygienic Working Environment**
    - Wash your hands frequently with soap and water for at least 20 seconds, use sanitising gel where hand washing is not possible, or not available, and especially:
        - After touching any "high touch" surfaces (door handles, shared kitchen appliances, photocopiers and other shared office equipment)
        - Prior to, and after, eating
        - Prior to, and after, smoking
        - Prior to, and after, using the toilet
    - Wipe down your workspace and equipment with disinfectant wipes or similar at the start of each day.
    - Don't share work areas, accessories, stationery or office supplies, computers, phones and other hand held devices.
    - Make the effort to wipe down touch points where possible (e.g. door handles and touch plates, etc.)
- **Physical Distancing – At All Times**
    - Adhere to the one way system at all times
    - Stay a minimum of 2 metres away from others – including in hallways, walkways, outdoor areas, etc. Markers are on the floor to give a visual indication of the 2 metre distance
    - Do not crowd or hover over someone at their workstation.
    - Do not congregate in common areas such as the car park, hallways, reception, café zero, toilets, kitchen areas, at printers, etc.
- **Lunch and Kitchen Areas**
    - Maximum occupancy is in place, so please limit your time in these areas as much as possible including the preparation of food/drinks or washing.
    - Note that the restrictions on eating at your desk have been relaxed.

    - Maintain a minimum 6 feet separation from others.
    - Do not share food or beverages, or bring open food platters to share.
    - Cups, plates, silverware and utensils have been temporarily removed from the kitchens. Please bring and use your own until further notice.
- **Toilets**
    - Adhere to maximum occupancy numbers.
    - ‘Toilet duck’ is available in all cubicles – please apply it after every use.
    - Ensure you close the toilet seat lid **before** flushing to prevent aerosol effect.

8. Visitors

- Only visitors deemed necessary for essential business meetings are permitted.
- All other visitors are deemed non-essential and are not permitted. Please continue to use Skype or MS Teams for meetings.
- Visitors for essential business meetings must be approved prior to attending head office.
- All visitors must complete a COVID-19 Self-Assessment Form at least one day prior to their scheduled visit.
- All visitors must be provided with a copy of this Return to Work Policy.

9. Respect for Others

- We understand that Covid-19 has been an unprecedented event in all our lives. It has required adjustment, lifestyle changes, and disruption to our normal ways of working.
- Some of our colleagues may have reservations about the impact that Covid-19 has or will have on their own situation, health, or wellbeing.
- We ask all staff and visitors to respect the feelings and emotions of others, as we apply the 'new normal'.
- Rest assured, we have planned for this return to the workplace and are committed to maintaining it in a way that respects our aspirations to 'Zero Harm'.
- Everyone has the right to come to work in a place that is free from harm and we expect and encourage everyone to raise health and safety concerns in the workplace, including in relation to the Covid-19 virus.

10. No Compromises

- Please make sure you and others follow this policy at all times.
- Challenge where necessary but be polite and respectful when reminding others to follow this policy.
- If anyone resists or repeatedly ignores the policy, please avoid confrontation and inform your supervisor and/or HR.

Every individual's safety is important.

We must all work together to keep everyone healthy and to help stop the spread of COVID-19.

G.4 Sign Up Sheet and Participant Information

Introduction
You are invited to take part in a research study, exploring how Augmented Reality (AR) can be used to guide users through industrial maintenance tasks.
This work will take place on site at Booth Welsh's head office in Irvine - due to current coronavirus restrictions, and to limit numbers on site this experiment is only open to those who would already be present for essential work purposes.
My name is Eleanor Smith, I am a PhD student in DMEM at the University of Strathclyde, and this study forms part of my PhD project, 'Industry 4.0 and Augmenting the Millennial Worker'.

If you are interested in taking part of either or both of these studies, please proceed to the next page and fill in your details.

End of Block: intro

Start of Block: privacy

Privacy Notice
This is a sign up sheet for volunteers to take part in an experiment using Augmented Reality instruction manuals. If you would like to take part in this experiment, please answer the questions below and enter your details on the next screen.

The personal data you provide here will be used to provide more information about participation in the studies. The legal basis for processing your information under the 2018 Data Protection Act is consent. Your personal information will not be shared with any third parties. Your personal data will not be linked to your performance in the study. You are free to withdraw or cancel your participation at any time. Once the experiment is complete, all personal data (name, email) will be erased.

If you have any questions, please contact me at eleanor.smith@strath.ac.uk. For data protection queries, concerns or complaints you can contact dataprotection@strath.ac.uk or visit the University web page regarding information security.

Please check the boxes below to confirm you have understood and agreed to your data being processed as explained in the Privacy Notice above.

- Yes (1)
- No (2)

End of Block: privacy

Start of Block: Contact

First Name
(optional)____

Surname
(optional)____

Email
Address____

End of Block: Contact

Start of Block: PIS

Consent Form

Name of department: Design, Manufacturing and Engineering Management **Title of the study:** Novelty and Learning Effects in Augmented Instructions **Please read the Participant Information Sheet** here **and answer the questions below:** Note: Unless you select all the options below, you will not be included in the study.

- I confirm that I have read and understood the Participant Information Sheet for the above project and the researcher has answered any queries to my satisfaction (1)
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences (2)
- I understand that anonymised data (i.e. data that do not identify me personally) cannot be withdrawn once they have been included in the study (3)
- I understand that any information recorded in the research will remain confidential and no information that identifies me will be made publicly available (4)
- I consent to being a participant in the project (5)

End of Block: PIS

Start of Block: RA SSOW

Risk Assessments and Safety Precautions
This work takes place at Booth Welsh head office in Irvine. Due to current coronavirus restrictions, additional safety measures have been implemented to reduce the risk of virus transmission, however it should be noted that the risk is not zero and you should not take part

if you do not feel comfortable.

Attached below are Risk Assessments for the experimental trials, which detail measures taken to reduce the risk of the COVID-19 virus being transmitted during this work. Please read them carefully, and if you are still happy to take part, acknowledge that you have read and understood them below.

Booth Welsh Return to Work Risk Assessment

Use of Shared Head Worn Devices Risk Assessment

Please acknowledge that you have read and understood the attached risk assessments.

- This response is to be recorded as my signature to the documents in place of a physical signature (1)

End of Block: RA SSOW

Start of Block: Demo

Background Questions
To help provide better context to my research data, I would appreciate if you could answer a few questions about who you are and what your background it. Like all the data collected throughout this process, it will be stored against a participant ID for anonymity. You do not have to answer these questions if you would prefer not to.

Age group:

- 18-25 years (1)
- 26-40 years (2)
- 41-65 years (3)
- 66 years and over (4)
- Prefer not to say (5)

Gender:

- Female (1)
- Male (2)
- Prefer not to say (4)
- Other (please specify) (5)
____

What is your current occupation, job title, or role?

____

Please rate your abilities/experiences using the scale below

	1 (1)	2 (2)	3 (3)	4 (4)	5 (5)	
Never used Augmented Reality	(	(	(	(	(	Expert user in Augmented Reality
Not at all comfortable with new and unfamiliar technologies	(	(	(	(	(	Extremely comfortable with new and unfamiliar technologies
No confidence in using IT and digital technology (e.g. PCs, smartphones, tablets)	(	(	(	(	(	Very confident in using IT and digital technology (e.g. PCs, smartphones, tablets)

End of Block: Demo

Start of Block: yes_consent

Thank you for agreeing to participant in this study - I will be in touch shortly to arrange everything. If you have any questions, please don't hesitate to get in touch with me at eleanor.smith@strath.ac.uk.

End of Block: yes_consent

Start of Block: No_consent

Without your consent, we cannot process your data to become a participant in this research. Thank you for your time.

Post-Experiment Survey

AR Trial Post Task Survey (BW)

Introduction

Thank you for taking part in this experiment, your input will be very useful for my research! Now you've completed the task, I just have a few questions for you to answer about your experience and an opportunity for you to give feedback. Remember you can download a copy of the Participant Information, including information about how your data will be managed, from my webpage: http://personal.strath.ac.uk/eleanor.smith/bw.html/.

If you wish to stay in touch, or here more about my research in future, do feel free to drop me an email at eleanor.smith@strath.ac.uk

---

Participant ID ____

End of Block: Intro/PID

Start of Block: Block 2

Mental Demand

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How mentally demanding was the task? ()								

Physical Demand

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How physically demanding was the task? ()								

Temporal Demand

	Very Low				Very High			
	0	3	6	9	12	15	18	21

How hurried or rushed was the pace of the task? ()	

Performance

	Perfect				Failure			
	0	3	6	9	12	15	18	21
How successful were you in accomplishing what you were asked to do? ()								

Effort

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How hard did you have to work to accomplish your level of performance? ()								

Frustration

	Very Low				Very High			
	0	3	6	9	12	15	18	21
How insecure, discouraged, irritated, stressed, and annoyed were you? ()								

End of Block: Block 2

Start of Block: More Qs

Do you think you made any errors whilst completing the task?
(if yes, please elaborate)

- No (28)
- Yes (please specify) (29) ____

Do you think you could perform that task again now, without the instructions

- Yes (24)
- No (25)

Do you have any other feedback on how this work could be improved?

____

____

____

____

____

End of Block: More Qs

Start of Block: Thanks

Thank you
Thank you for your time and effort in contributing to this research. If you have any questions or feedback, please don't hesitate to get in touch with me at eleanor.smith@strath.ac.uk.

End of Block: Thanks

G.5 Full Results Table

ID#	Outcome (hh:mm:ss)			NASA-TLX Score	Do you think you made any errors whilst completing the task?	If yes, please elaborate	Do you think you could perform that task again now, without the instructions	Do you have any other feedback on how this work could be improved?
	Failure	Partial Success	Success					
601	00:16:55			2.833333	Yes	on the initial pick, I should have moved the arm furtherout to avoid the obstacle	Yes	no
602		00:15:16		7	Yes	Didn't chart the path correctly on the first go- should have utilised the AR on the phone more.	Yes	Was a bit unclear that I was supposed to physically press the buttons on the robot in the beginning.
603		00:09:04						
604		00:19:33		9.833333	Yes	Did not correctly anticipate the movement of the robot between points	Yes	
605		00:09:30		0.00660	Yes	Didn't read instructions fully at first.	Yes	Video instruction may have been better than written word?
606			00:14:13	5.5	Yes	Not familiar with the buttons erc	Yes	Improvement of image on phone
607			00:09:24	5	No		Yes	
608			00:22:11					
609		00:13:58						

610	00:14:34						
611	00:15:08		0.833333	Yes	I had to adjust the height of the arm to go higher	Yes	once I figured out what I was doing it was easy, I think a quick summary before the start would help saying you are going to manually move the robot arm and record its steps you need to pick up the object and drop it in the virtual pot. the following instruction will guide you throw the process.
612	00:09:21		6.333333	Yes	did not lift the robot arm high enough	Yes	No was very well thought out