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Flinders University
Australian Industrial Transformation Institute

# Staying on course

## Human factors in navigating digital work orders in harsh environments in shipbuilding


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Australian Industrial Transformation Institute



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# Key findings

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| **Context** | **Human factors and ergonomics (HFE)** explores the interaction between humans, their work and the environment in which it takes place (including the tools and equipment involved), aiming to deliver productivity and wellbeing improvements through deep understanding of the experience and capabilities of the human.<br><br>**Digital work orders (DWO)** have the potential to make information available at the time and point of use, thereby increasing productivity by reducing downtime, multiple handling of information, errors, and miscommunication. Digital technologies play a crucial role as an enabler that supports users to effectively access DWO. Digital technologies provide different benefits and limitations depending on environments, tasks and work characteristics. Low complexity **pipe and instrument tasks** performed in simulated harsh environments (**at heights, constrained and simulated confined spaces**) were used to evaluate potential benefits of digital technologies, comparing a **smart phone** (Apple iPhone) with augmented reality (**AR) Google glasses**, requiring users to emulate activities involved in typical work processes (e.g., capturing photos, entering and retrieving data). In addition to task performance measures, trial participants provided a range of feedback relating to their experience of the tasks while using the technologies within the broader work environment.<br><br>The results and insights provided here are based on the experience of 24 users (n=2 female) employed by the **shipyard and small and medium-sized manufacturing enterprises (SMEs) in Adelaide, South Australia.** Participants' ages ranged from 21 to 52 years and the average years of experience in the construction and manufacturing industries was 11 years, ranging from 1-35 years. |
| **Performance outcomes** | **Usability:** The phone was most preferred device for ease of reading, especially when working at height, which was identified as the easiest workspace. Readability was rated least easy when working below the module in the confined space (which was also identified as the most difficult workspace). There were no significant differences between phone and glasses for other usability measures including ease of data entry and retrieval, comfort, physical demands and device suitability for task.<br><br>**Time:** Performance time was significantly faster using the iPhone compared to the Google glasses. During this trial, there was a significant task learning effect where performance time on each device took significantly longer when using that device for the first time.<br><br>**Productivity and quality:** Performance with the Google glasses produced more errors due to 1) different user interface in the software design, 2) smaller size of display, and 3) low familiarity with the device and its interaction modes (gestures and voice commands). Novelty may also have been an issue as fewer errors were made with whatever device was used second due to the advantage of learning from previous task performance.<br><br>**Safety:** The iPhone had more potential issues including 1) incompatibility of gloves with the screen, inhibiting scrolling and typing and leading to frequent removal and reapplication of gloves, 2) carrying and securing a phone while moving, climbing and working, 3) needing to repeatedly pick it up and place it down. Potential issues with the Google glasses included 1) various visual problems including difficulty in focusing causing squinting, awkward neck postures and upward gaze. Another significant safety issue was 2) reports of distraction and reduced situation awareness, where participants reported being more focused on the projected information than aware of their immediate surroundings. |

| | |
|---|---|
| **User feedback** | **Device suitability:** The iPhone has significant potential in industrial environments, and a high level of familiarity due to its popularity. However, participants considered the phone to be fragile in harsh environments and required a fastening or carrying case to limit need to continually place it down when hands-free performance was required. Conversely the Google glasses have touchpad and voice recognition features, allowing hands-free capability. Being a wearable device, the glasses had a low impact on the range of movements required and participants found the glasses reasonably comfortable to wear. A disadvantage of the voice recognition with the glasses was its limited effectiveness in noisy environments. Participants considered that the glasses would be better suited to more active and complex tasks such as cable harnessing and pipe fit out. A drawback of the glasses was that frequent movement of the head and body altered the location of the glasses display.<br><br>**Comfort and ease of use:** The iPhone has good readability and familiarity but required compatible safety gloves for effective use. Glasses were light to wear, but the display was too small, requiring a high level of concentration, increasing discomfort and eye strain. The amount of information that can be displayed on one screen was extremely limited, requiring repetitive scrolling.<br><br>**Readability:** Glasses were more affected by the contrast between the screen brightness and natural light.<br><br>**Learning effects:** Most participants were highly familiar with the phone as opposed to glasses which were novel for all participants who had no prior experience with augmented reality glasses. |
| **Key HFE principles** | **The trial emphasises the following key HFE principles:**<br><br>*Effective performance is dependent on the fit between the user and the design of the work tasks, technologies, tools and environment.*<br><br>• The fit of the glasses emphasised several individual characteristics including visual abilities and anthropometry to ensure correct fit on the face – these factors were significant limiters to performance.<br>• The design of the user interface did not adequately protect against error behaviours and allowed users to unintentionally miss completion steps and exit the work order.<br>User testing of the software before implementation would identify these shortcomings.<br>• The physical environment had an impact on readability with the glasses in darker environments, reducing user satisfaction and ratings of device suitability.<br><br>*Introduction of new technology has impacts for job design*<br><br>• Harsh environments are difficult workplaces and require careful attention to job design to avoid health and safety impacts. Several participants reported the glasses to be acceptable for short periods of use.<br>• Use of the phone created frustration in having to handle it continually, making it potentially frustrating over a long period of work. The phone required fastening to the body to minimise manual handling risks<br>• Accessing a digital work order fundamentally changes how information is presented, how data is entered and retrieved and communication between co-workers and supervisors.<br><br>A digital work order increases transparency and traceability of work performance, also influencing job and task design and working relationships. |

# Recommendations

To promote the uptake of digital work order technology in the shipyard and along the manufacturing supply chain, the following recommendations arose from this trial in harsh environments:

**Recommendation 1**: Business cases are needed which incorporate opportunities to improve business performance, particularly the HFE impacts on the workforce undertaking 'demanding, dirty and dangerous' work. Cost benefit should also include the savings related to improved productivity, reduced administration costs and the prevention or minimisation of injury, absenteeism, and dissatisfaction.

**Recommendation 2**: Business cases can be informed through conduct of technology trials adopting HFE research methods. This should be undertaken in situ (where possible) in collaboration with researchers and business. Where possible, findings should be shared internally within the business to support business development and change management and externally to share and learn from the experience of others.

**Recommendation 3**: Real world trials are particularly important to assess aspects of usability in harsh environments. Portable digital devices for use in harsh environments require ruggedised cases (for phones) and storage pouches when not in use. Suitable storage and fastening methods need to be designed in consultation with end-users to enhance usability. Different methods of activation (voice, gestures, touch) are required to provide alternatives in different environments and in situations where hands-free use is required due to task demands. Suitable gloves should be trialled to ensure compatibility with touch screen activation. In situ trials allow for the assessment of durability, reliability, and connectivity. Battery life should also be considered as a factor in usability in real world trials.

**Recommendation 4:** Other AR technologies (e.g., Realware and Zebra AR) should be trialled in harsh environments to overcome some of the limitations with the Google glasses. Realware AR has ruggedised features and incorporates safety glasses and is compatible with hearing protection and hard hats so would be potentially more suited to harsh environments. Zebra AR can be connected to an Android smartphone that provides more flexibility within an organisation's total digital ecosystem so would be more suited to larger organisations requiring a high level of integration.

**Recommendation 5**: Portable digital device and software manufacturers working with representative end-users must design features of devices and software to ensure ease of use. Devices and software should comply with usability standards such as ISO 9241:2018 *Ergonomics of human-system interaction* and design usability heuristics ( e.g. Endsley et al., 2017). Key principles include:

- fit with user environment and task,
- form communicates function,
- minimise distraction and overload,
- adaptation to user position and motion,
- alignment of physical and virtual worlds,
- fit with users' physical and perceptual abilities,

- accessibility of off-screen objects, and
- account for hardware capabilities to achieve optimal integration.

**Recommendation 6**: The workforce must receive adequate instruction, training and supervision during the introduction of new technology. Successful introduction requires procedures for device allocation, checking in and out, hygiene, maintenance and servicing of devices. Users of AR technology should have a vision assessment and be individually fitted for devices. AR technology must be trialled to ensure compatibility with standard PPE used in manufacturing environments.

**Recommendation 7:** Organisations and leaders require a greater understanding of the principles and practices involved in effective change management. Key principles include:

- Clearly articulate the reasons for change, who is likely to be impacted and how, and promote a vision.
- Communicate key information, share information often and involve workers in the process.
- Listen carefully and respond sensitively and promptly to worker's feelings and concerns.
- Provide training (both technical, e.g. DWO content and process, AR gestures and commands), and individual development, (e.g. opportunities to acquire new skills) and allow time for workers to trial and learn the technology without expecting rapid high productivity.
- Seek ongoing feedback from the workforce throughout change to identify and address any unexpected issues early.

**Recommendation 8:** Government, business, industry associations, technology providers and researchers can all play a key role in educating and raising awareness of the potential benefits and challenges of new technology. Development of collaborative centres, such as the Line Zero Factory of the Future enable SMEs to trial technology on applications they need. Such collaborations provide opportunities for active learning and confidence building to translate trials to implementation, accelerating the uptake and diffusion of technology. An important starting point is for enterprises to optimise existing processes first by auditing to ensure they add value. Matching technology to processes, people and contexts is the next step for delivering efficiencies.

# Contents

## List of Figures



## List of Tables

# Preamble

Australian manufacturing is a vital contributor to the Australian economy, accounting for 11% of annual export income and investing significantly in research and development (AI Group, 2019). While the sector has faced considerable competitive pressure over the last decade, substantial investment in the Australian maritime shipbuilding sector is a catalyst for rapid growth in low volume, high-value manufacturing over the next five years. BAE Systems Maritime Australia (BAESMA) is at the centre of this resurgence through the Hunter Class Frigate program.

This report is one outcome of a major research partnership between BAESMA, Flinders University and the Innovative Manufacturing Cooperative Research Centre (IMCRC) - a not-for-profit initiative of the Commonwealth of Australia. The IMCRC has partnered with Flinders University and BAESMA to conduct research into accelerating the uptake and diffusion of Industry 4.0 (I4.0) in shipbuilding and the Australian manufacturing industry. This multi-year collaboration involves the application of a human factors and ergonomics (HFE) approach to the adoption of advanced technologies.

The success of technology adoption is largely dependent on its acceptance by a variety of end-users (including the workforce, business owners and the supply chain). The ease of use of the human-machine interface is a pervasive and fundamental component of I4.0 technologies. HFE significantly contributes to successful uptake and diffusion through people-centred design and evaluation to ensure technology is fit for purpose. A significant benefit, I4.0 technologies possess inherent adaptability which creates ongoing opportunities for application in low volume and high mix manufacturing settings, including shipbuilding. Digital work orders have been identified as a key opportunity to connect workflows using I4.0 technologies including the ubiquitous smart phone and more advanced technologies like augmented reality. Harnessing these technologies has the potential to transform work processes to improve productivity, job design and safety in harsh (‘demanding, dirty and dangerous’) work environments.

This report presents findings of a research trial comparing use of portable digital technologies to access a digital work order in simulated shipbuilding harsh environments. It utilises a combination of methods that draw on human performance outcomes that might be readily applied in assessing the impact of new technologies in a range of manufacturing contexts.

It is anticipated that the outcomes of this trial will provide HFE (and some technical) insights of value to those enterprises currently utilising digital work orders, and to those considering the potential adoption or extension of this technology.

We extend our thanks to all those who participated in the trial.

**Professor John Spoehr,**

Director,

Australian Industrial Transformation Institute

Our lead industry partners, BAESMA, involved in the implementation of this project include Sharon Wilson (Continuous Naval Shipbuilding Strategy Director), Evangelos Lambrinos (Exports and Innovation Manager), Andrew Sysouphat (Principal Technologist - Hunter Class), Ivor Richardson (Project Manager – Strategic), Derek Morton (Project Manager – Industry 4.0 Trials), and Mark Francis (Project Manager). Rebekah Taylor (BAEMSA Research and Technology intern) assisted in the software development of the digital work order. Collectively we thank the Board of the IMCRC and David Chuter, CEO for their support for this project. We share their vision for growth of advanced manufacturing in Australia.

# 1 The role of human factors in technology adoption

## 1.1 The human factors approach

New technology captures the imagination of potential users with the promise of new experiences that enhance performance and satisfaction. It is often assumed that technologies are designed to be fit for purpose, but new purposes are constantly emerging with the objective of making work more effective and sustainable. Human factors and ergonomics (HFE) examines the interactions between humans, their tasks, tools and the environments in which their activities arise, with the goal of optimising the effectiveness of these interactions. The human is viewed as the centre of the system, which ideally supports them to achieve their goals (Stanton, Salmon, Walker, Baber, & Jenkins, 2017). Thus, the purpose of HFE is to optimise productivity, quality, safety and satisfaction, and ensure sustainable performance for individuals and enterprises through fitting tasks to the capacities and limitations of people (O'Keeffe, Moretti, Howard, Hordacre, & Spoehr, 2020).

HFE focuses on understanding the performance implications of human capacities and limitations (e.g. sensory processing, mental and physical workload, judgement, and social behaviour), and values the end-user perspective of using a product or system. Consequently, highly participatory methods that tap users' deep experience are the hallmark of HFE practice (Burgess-Limerick, 2018). Methods draw upon observations to reveal behaviours in context, self-report surveys to allow people to share their insights, and task analyses that allow decomposing task performance to understand problem solving, error management and sources of workload (Cresswell, Blandford, & Sheikh, 2017).

In terms of digital work management, HFE considerations are largely assessed through the concept of usability. The International Standards Organisation defines usability as:

> *[T]he extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use (cited by Bevan, Carter, Earthy, Geis, & Harker, 2016 p. 269).*

Drawing on diverse HFE methods, usability testing is widely applied in evaluating the effectiveness of digital technology. Usability assesses the total experience of use, including the integrated performance of hardware with software, where hardware acts as the vehicle for accessing information. Usability testing has growing application to digital work management systems, particularly the effectiveness of a digital work order (DWO).

DWOs guide workers through a work process and aim to reduce complexity by supporting cognitive processing by presenting information clearly and consistently. A well designed DWO also has the benefit of improving worker performance and satisfaction (Palmqvist & Vikingsson, 2019). Understanding how end-users interpret information and navigate the device (e.g. through touch, voice, gestures) are fundamental to determining whether a technology is fit for purpose. Context of use is also a critical consideration, with work environment influencing ease of interaction and determining reliability and durability of hardware.

In shipbuilding, production processes increasingly require the same high level of planning and control seen in one-off production, given shipbuilding involves high mix and low volume manufacturing (Toivonen, Järvenpää, & Lanz, 2017). DWO have the potential to contribute to meeting these demands and enhance competitive advantage by promoting efficiency, error elimination, safety, transparency and connectivity of information across the enterprise (Onar & Ustundag, 2018). The value proposition presented by DWO enables flexibility in production through improved quality of information, targeted quality control, real-time process control, worker specific instructions, improved traceability, automated data collection and the development of analytics (Toivonen et al., 2017).

This report aims to provide research insights that inform the successful adoption of technology to enable effective interaction with a DWO. New technology will inevitably change the design of work and processes, so this report also presents recommendations to guide technology implementation through successful system and work design. Findings integrate multiple data sources to summarise performance measures and participant experiences of using smart phone (Apple "iPhone") and augmented reality glasses (Google glasses) technologies to access a DWO in simulated harsh environments. The report concludes with recommendations to accelerate the uptake of these technologies in the shipyard and across manufacturing more generally.

This research views the system of work through a HFE lens and provides recommendations to guide the successful implementation of technology. While the research outcomes inform the value proposition of technology adoption, and the opportunities for new business models, extensive analysis of these factors is beyond the scope of this project.

## 1.2 Digital transformation - value and challenge in industry

### 1.2.1 The opportunity presented by digital transformation

Paper-based processes have been ubiquitous across industries where work involves schedules, work orders, specifications, instructions, and reports. Countless hours have been spent dealing with printed information in every single business process. McKinsey reported that employees spent around 1.8 hours every day, averaging 9.3 hours per week, on searching and gathering paper-based information, without contributing any value (McKinsey, 2012). Although this paper-dependent work still exists, many organisations are transforming their processes and structures with advanced digital technologies to become 'digital organisations' capable of meeting their client's needs by delivering high-quality products (Setia, Setia, Venkatesh, & Joglekar, 2013), referred to as 'digital transformation'.

Digital transformation (DT) is defined as "the transformation of business process, culture, and organisational aspects to meet market requirements, owing to digital technologies" (Nasiri, Ukko, Saunila, & Rantala, 2020 p. 2). In other words, "it is the rethinking, reimagining, and redesigning of business in the digital age" (Pramanik, Kirtania, & Pani, 2019 p. 2). DT involves a significant change in business process including digitising (Hagberg, Sundstrom, & Egels-Zandén, 2016), massive data collection from different sources (Frank, Dalenogare, & Ayala, 2019), greater network capability (Matt, Hess, & Benlian, 2015), efficient customer interfaces (Pramanik et al., 2019), and digital information exchange using digital technologies (Frank et al., 2019). Successful DT can be an opportunity to transform business processes (Moeuf, Pellerin, Lamouri, Tamayo-Giraldo, & Barbaray, 2018) through offering new business models that enable more effective engagement with customers at every point, increasing client satisfaction (Ezeokoli, Okolie, Okoye, & Belonwu, 2016). One of the greatest benefits from digital technologies is ever-optimised data (Mohamed, 2018), allowing increased flexibility, individualised customisation, dynamic resource allocation, and reduced complexity (Mohamed, 2018). Long term benefits for business performance include greater efficiency, productivity, quality, communication, safety, data management and work optimisation (Aghimien, Aigbavboa, Oke, & Koloko, 2018).

### 1.2.2 Knowledge management

Poorly managed information may have a detrimental impact on the productivity of organisations and individuals (Ben-Arieh & Pollatscheck, 2002). DT enables organisations and workers to share and use knowledge more efficiently through enabling digital technologies, potentially capturing collective knowledge that may be lost with staff turnover, and allowing easier updating than available with paper-based documentation. Effective information flow is critical in optimising worker performance and productivity (Laschinger, Finegan, & Shamian, 2002), significantly influencing job satisfaction (Palvalin, Vuori, & Helander, 2017). Efficient knowledge sharing supports workers to plan and perform tasks faster and with better quality (Wu, Huberman, Adamic, & Tyler, 2004). Enterprises within an industry or supply chain may also benefit from digital technology adoption that enables knowledge exchange with internal and external entities. Many studies emphasise the significance of collaborative capabilities in manufacturing industries, where stakeholder engagement can enhance resource accessibility, improving productivity (Klein & Vella, 2009), sharing risks (Kogut, 1988), and increasing profitability (O'Toole & Donaldson, 2002).

### 1.2.3 Profit, productivity, quality, and safety

The SAP Centre for Business Insights and Oxford Economics (SAP, 2021) report that 80% of organisations have achieved increased profits through DT and 85% increased their market share. The McKinsey Global Institute (McKinsey, 2012) found that adopting digital management typically increases productivity by up to 25% (Saunders, 2019) by transforming manual tasks, integrating data (Virtru, 2020) and utilising cloud technology (Crnjac, Veža, & Banduka, 2017).

DT connects devices allowing communication enriched through various sensors and computing systems that enhance project efficiency and planning (Oladokun, Asuquo, & Adelakun, 2021). Data richness enables improved efficiency and quality supporting decision making, reducing human errors, and improving safety, health and environmental outcomes (Beatty, 2017). Connectivity amongst different technologies allows organisations to update real-time information to inform predictive maintenance in high risk, high importance processes and supports quality assurance (Beatty, 2017).

### 1.2.4 Engaging with digital transformation

The potential value of DT has drawn worldwide attention across industries. However, technology implementation is highly complex, and is likely to profoundly change jobs and processes, with significant social implications for people's interactions and communication (Büyüközkan & Göçer, 2018). As technology enables greater connectivity, more elements including people and processes interact than ever before. Concurrently, digital technologies become increasingly interconnected to services and products and almost inseparable from their fundamental IT infrastructures (Bharadwaj, El Sawy, Pavlou, & Venkatraman, 2013). Many enterprises fail to realise the need or possess the knowledge and evidence to change their traditional working conditions or methods despite newly adopted technologies creating demands for integration (Scuotto, Caputo, Villasalero, & Del Giudice, 2017). Common barriers to change are unrealistic expectations of information technology performance, and inadequate training and support (Riege, 2005). Limitations within the technology itself include poor usability and frequent failures that negatively affect acceptance by users (Tarafdar, Tu, Ragu-Nathan, & Ragu-Nathan, 2011). Organisational transformation is complex and takes time, requiring careful consideration of how the enterprise should adapt and transform to realise the potential value of DT (Dörner & Edelman, 2015). A DT journey begins with identifying the demand for change, and the potential efficiencies, savings and opportunities for improved knowledge management. Digitising poor processes will not yield the desired benefits, so optimising processes to ensure they add value is a key early step. Consulting and involving end-users of the process is essential to secure their engagement and commitment so vital to success (Broday, 2020). Strategy, infrastructure, and capability to embark on a long-term transformation journey (Srai et al., 2016) are key considerations for enterprises seeking to realise the value possible through successful DT (Büyüközkan & Göçer, 2018).

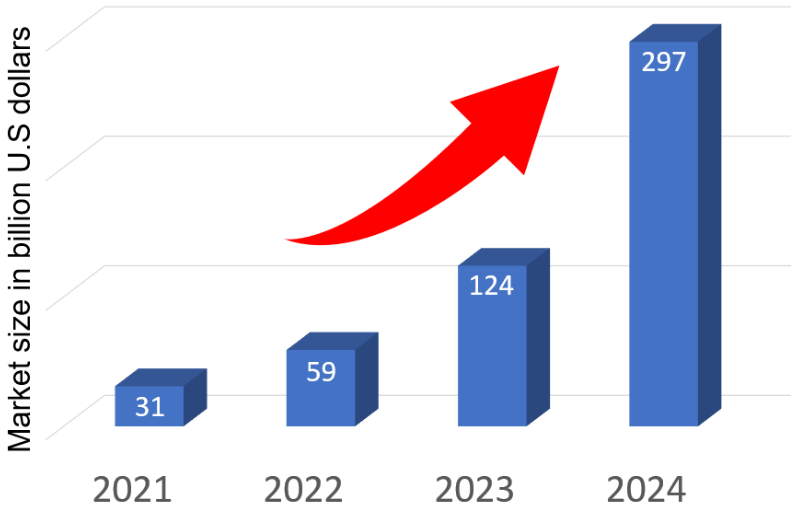
## 1.3 Introduction to augmented reality technologies in industry

### 1.3.1 Augmented reality technology and market growth

Augmented reality (AR) is a technology that enables people to access virtual 2D or 3D data (i.e, images, text, audio, video, or information) overlayed on their view of the real world. AR provides users with a highly immersive experience (García-Pereira, Portalés, Gimeno, & Casas, 2020) and enhances their perception of interaction with the real world (Azuma, 1997). The AR experience is closer to 'reality' than 'virtual reality' because it uses a real environment as a starting point and augments it with other components (Van Kleef, Noltes, & van der Spoel, 2010). AR utilises a variety of sensors including computing components, cameras and a display device (Hassan, 2019). Typically, devices are wearables such as headsets or glasses, which have value in enabling hands-free operation and minimise the need to look down and search for information as is required with hand-held devices.

DT is enabling AR (and VR)-related industries and markets to grow rapidly. The global market value of AR and VR industries is forecast to approach USD $300 billion by 2024 (Figure 1). In line with this trend, the AR smart glasses market is expected to grow by USD $69 million between 2021 and 2025 (CISION, 2021), with head-mounted display device sales expected to increase by almost 20% through 2022 (Gartner, 2018).

**Figure 1-AR/VR market size worldwide from 2021 to 2024 (Statista, 2021)**




### 1.3.2 Human factors implications of augmented reality technologies

AR technologies can be hand-held (e.g., phones) or wearable (e.g., glasses). Wearable AR technology is perceived to provide comfort and efficiency for the end-user, minimising the manual handling associated with hand-held devices. By definition, wearable AR technology requires close contact with the user, potentially interfering with normal function, including movement and vision (Kim, Nussbaum, & Gabbard, 2016), leading to annoyance and potential safety risks (Grier et al., 2012). A significant benefit of using AR technologies is their mobility, however walking and climbing while using AR have been found to increase performance time due to dividing attention between the real and virtual worlds (Mustonen, Berg, Kaistinen, Kawai, & Häkkinen, 2013; Woodham, Billinghurst, & Helton, 2016).

AR aims to augment human cognition by presenting real-time information directly to the senses. While the benefits are potentially immense, (e.g. a multi-dimensional understanding of complex data and faster navigation), there is also potential for failure if AR technologies overtax sensory and cognitive capacities, impeding performance and inducing errors (Endsley et al., 2017). The challenge for the end-user of AR technology is the integration of two different environments: the real physical world, with the computer-generated world visually projected on top. Assimilating the real and virtual environments may lead to greater information processing to constantly reconcile the different symbols, structures, and dynamics in each world (Grier et al., 2012). Lag between user movement and displayed movement of digital objects may result, increasing perceptual load and creating distortions through poor image resolution. Distraction can become a key safety issue leading to impaired situation awareness, where users pay greater attention to the display than to their real environment (Grier et al., 2012).

Integrating two different mental environments (the projected and the real) represents a dual task activity involving parallel information processing. Hand-held devices enable users to choose when they will glance at their device, while AR projecting information on the field of vision does not (Klose, Mack, Hegenberg, & Schmidt, 2019). The constancy and closeness of the projected image to the eye may lead to information processing overload, suggesting the advantages of AR technology are limited by the capacity of human cognitive abilities (Klose et al., 2019). Factors influencing the quality of task performance include task difficulty, and the level of real task similarity to the perceptual and processing modalities used to interact with projected information (i.e. there is consistent mapping of visual and auditory requirements between the two worlds). Consistency is also needed to help the end-user prioritise actions and switch between tasks. The compatibility of the two task worlds in terms of information, material or routines helps to minimise workload and prevent mismatches likely to lead to confusion.

Various measures are applied to assess human performance using AR technology. Typical data collected include reaction and performance times, accuracy, error patterns and recovery strategies, information comprehension and retention. Where more cognitive resources are used for attention, interpretation and building mental models, the information is more likely to be retained (Klose et al., 2019). Since the user experience is a key factor in assessing the effectiveness of technologies, subjective ratings of readability, comfort, workload, perceived distraction, and preferences provide valuable insights. Free text comments provided as part of surveys, interviews or debriefs also provide nuanced information about the user’s perspective on usability.

Smart phone and AR glasses technologies have previously been compared with paper maps for their usability and effectiveness in the completion of indoor navigation tasks (Rehman & Cao, 2016). The glasses were perceived to be more accurate than the phone, and other measures found no significant difference in performance between phone and glasses. Use of the phone resulted in greater errors which were attributed to participants generally holding the phone around mid-body level to view thereby having a wide viewing arc which slowed performance and contributed to greater errors. Holding the device closer is likely to assist in better definition of icons on the screen, supporting participants to recognise features in a display and making more accurate interpretations. Use of the paper map produced significantly slower performance than both devices. Notably using both digital devices for navigation resulted in worse route retention than using the paper map, due to the time taken to process information. The mental workload of orienting the self, relative to the static representations on the map, involved greater engagement with the information, enhancing memory and retention.

The potential for uptake of AR technology was explored in a survey of ninety early adopters and experts in user experience (Koelle, El Ali, Cobus, Heuten, & Boll, 2017). The most frequently perceived advantages of AR glasses were hands-free use, situated information access and a natural feeling of interaction. Participants anticipated AR glasses to be most successful in specialised workplace applications, including the military, healthcare, electricity and utilities, construction and manufacturing. AR glasses were thought to provide advantages in aiding performance in procedural and navigation tasks both in occupational and general use settings. Factors cited as most likely to impede adoption included lack of suitable use cases, poor comfort leading to ergonomic issues (awkward postures, restricted movements) and lack of usability (readability, ease of data entry and retrieval, use of gestures). AR is likely to add value to training in applications that augment real world scenarios, particularly in high-risk contexts. The challenge in training design is to develop an accurate understanding of the user state in real time. Eye tracking and EEG[1] have been used to assess cognitive performance deficiencies (e.g. scanning, detection or recognition) in order to improve design and better support performance (Grier et al., 2012).

### 1.3.3 Augmented reality technology benefits and application

Significant market growth has been possible due to industry acknowledgement of the multiple benefits of AR applications. Various industries are taking advantage of AR solutions in practice including the manufacturing, construction, warehousing and energy sectors. AR can play a crucial role in reducing task complexity and improving quality, productivity and customer satisfaction during the entire project life cycle from design to operation. For example, in the design phase, AR can be used to facilitate effective design processes (Elia, Gnoni, & Lanzilotto, 2016), enabling stakeholders to easily examine, test, and evaluate prototypes in dynamic ways using simulated AR visualisation. This capability enables reviewing physical prototypes in depth by merging virtual and real elements, saving time and costs (Rejeb, Keogh, Wamba, & Treiblmaier, 2020). Closer engagement between designers and customers becomes possible by visualising and contextualising products, and better understanding client needs (Rejeb et al., 2020).

In manufacturing operations AR glasses provide visual information including the locations of individual parts and detailed specifications, improving quality management (Rüßmann et al., 2015). Wearing AR glasses can enhance operators' skills and knowledge through accessing task-related information directly in real time and work conditions, allowing better instruction and monitoring (Knauer-Arnold, 2020). These benefits allow businesses to integrate workflows for more efficient operation and have been implemented in warehousing (Reif, Günthner, Schwerdtfeger, & Klinker, 2010), transportation (Pokrić, Krco, & Pokrić, 2014), and logistics (Berkemeier, Zobel, Werning, Ickerott, & Thomas, 2019).

AR technologies can be effectively used for remote maintenance activities in harsh environments, improving worker safety (Elia et al., 2016). AR technologies can also inform predictive maintenance from sourcing operational information on equipment including technical elements (Rejeb et al., 2020). For example, a real-time monitoring system with AR can integrate the entire lifecycle data of equipment that streamlines workers' maintenance tasks (Liu, Jiang, Gao, & Wang, 2018). These advantages have resulted in significant business improvements in various industries as shown in Table 1.

[1] An electroencephalogram (EEG) detects electrical activity in the brain.

**Table 1- Business improvements with AR application**

| Industry | Improvements |
|---|---|
| Manufacturing | • "Boeing Aviation cut its wiring production time by 25% and reduced error rates effectively to zero" (Upskill, 2021). |
| Construction | • 75% reduction of errors on assembly tasks and 90% time saving for developing the same type of prototype (Wang, Wang, Sepasgozar, & Zlatanova, 2020).<br>• Monitor quality of precast elements and make photographic, scanned 3D model, and stroke-type annotates with the AR-based tool (Wang et al., 2020). |
| Warehousing | • Error minimisation in identifying products (Kretschmer, Plewan, Rinkenauer, & Maettig, 2018).<br>• Increased efficiency and productivity through reducing order picking including search time, fatigue, errors (Kretschmer et al., 2018).<br>• GE Healthcare achieved "46% improvement in order completion speed in its first days" (Upskill, 2021). |
| Energy and utility | • Provide better training, manage inventory efficiently, generate data sources (Hassan, 2019). |
| Telecom | • 5% faster completion times, 11% lower operating costs and a work error rate improvement of 17% (Upskill, 2021). |
| Training | • Participants retained information longer when trained with AR, an aspect which may directly influence assembly quality (Macchiarella & Vincenzi, 2004).<br>• AR required shorter completion time for a gully trap assembly task than paper-based work. Especially, learning phase was shorter with AR-supported training (Hořejší, 2015). |

# 2 The digital work order trial in harsh environments

## 2.1 Trial background and aims

Digital work orders (DWOs) are being adopted across a variety of industries, including healthcare, trades services, building management and manufacturing (Gheisari & Irizarry, 2016; Neges & Koch, 2016; Pimminger, Neumayr, Panholzer, Augstein, & Kurschl, 2020). DWOs have the potential to make information available at the time and point of use, thereby increasing productivity by reducing downtime, multiple handling of information, errors, and miscommunication. Different digital technologies can be used to support and access DWOs. Previous trials conducted by the BAE Systems Maritime Australia Research and Technology team (BAESMA R&T)[2] assessed three hand-held digital devices in simulated harsh environments to assess usability and durability. Results of that trial indicate 54% of users preferred the Apple iPhone to the Apple iPad (27%) and Microsoft ruggedised tablet (14%) for ease of use in accessing instructions and submitting work. Feedback highlighted the need to hold hand-held devices was a significant shortcoming. In the current trial[3], AR glasses, a hands-free device, were compared to the Apple iPhone to assess the potential benefits of hands-free operation in simulated harsh environments.

The trial aims were to:

- assess the usability of smart phone and AR glasses technology in accessing a DWO in typical shipbuilding tasks simulated in three shipbuilding harsh environments (working at height), in a constrained space (inside the module) and in a confined space[4] (in the cavity below the module),
- evaluate potential productivity and quality impacts, and
- determine impacts on user safety, particularly during manual task performance.

The trial process and duration are summarised in Figure 2. Participants typically took between 50 and 85 minutes to complete the trial process.

[2] O'Keeffe, V., Howard, S., Hordacre, A.L. & Spoehr, J. (2021). *Usability of portable digital devices in harsh environments*. Unpublished Summary Internal Data Report for BAESMA. Adelaide: Australian Industrial Transformation Institute, Flinders University of South Australia.

[3] Flinders University Human Research Ethics Committee Approval Number 4159

[4] Note that a confined space has specific meaning under work health and safety law and is a space not intended to be occupied by a person. See https://www.safeworkaustralia.gov.au/sites/default/files/2020-08/model_code_of_practice_confined_spaces.pdf

**Figure 2: The five key phases of the DWO trial in harsh environments**

**Research administration requirements:**

Completion of COVID-19 checklist and hand sanitisation, informed consent, and safe work procedures

(*10 minutes*)

**Complete work order with first device**

Familiarisation with device and work order.

Collection of PPE, tools & parts. Completion of work order in <u>one</u> assigned work location

*(20 minutes)*

**Online survey:**

Provide perceptions of, and feedback about use of device for task and work conditions in harsh environments

*(10 minutes)*

**Complete work order with second device**

Familiarisation with device and work order.

Note glasses had longer familiarisation time due to novelty

Collection of PPE, tools & parts. Completion of work order in same work location as for first device

(*30 minutes*)

**Online survey:**

Provide perceptions of, and feedback about, device for task and work conditions in harsh environments

(*10 minutes*)

*Note, task order was randomised.*

## 2.2 Methodology

The trial design adopted a repeated measures methodology where each participant completed the trial task using both the phone and the glasses. The order of device used first was randomised to minimise recency effects (where the method repeated last may influence performance and evaluation of the overall experience). Twelve of the 24 participants completed the glasses trial task first.

The study was designed to assess the two digital devices in three locations simulating typical shipbuilding harsh environments – working at height, in constrained space, and in a confined space. Each participant completed the task trial using the phone and the glasses in the same location. Selection of location was randomised to ensure even distribution of participants across locations (see Table 2). Notwithstanding this, researcher discretion was used to re-allocate participants from the confined space or at height locations where they were identified to have pre-existing vulnerability to injury from accessing the height or confined space locations.

**Table 2: Summary of study design**

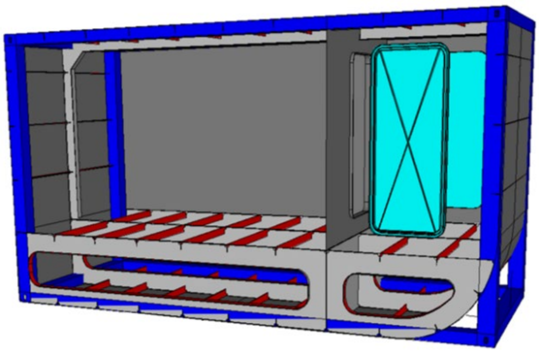
| | At height | Constrained space | Confined space | Total |
|---|---|---|---|---|
| Phone | 4 | 4 | 4 | 12 |
| Glasses | 4 | 4 | 4 | 12 |
| Total | 8 | 8 | 8 | 24 |

In accordance with principles for rigorous and practical study design, the trial was piloted with Flinders University and BAESMA R&T members to assess the feasibility and relevance of the trial activities, resources and data collection and management procedures (Doody & Doody, 2015). No changes were made to the trial protocol as an outcome of pilot activities.

The selected work locations were simulated in a mini-module located in a semi-industrial environment called ‘Pilot Factory of the Future’ (PFoF) - Line Zero. This facility provided a controlled, safe environment where measurement could be undertaken with limited interruption. Mini modules were designed and built to simulate real-life harsh conditions like shipbuilding and manufacturing environments as shown in Figure 3 and Figure 4.

**Figure 3-Initial mini-module (Photo)**

**Figure 4-Initial mini-module (3D Model)**

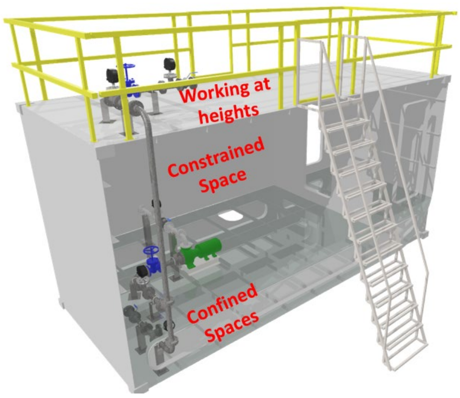


*Source: AITI Photo Stock 2021*

To conduct a practical and realistic trial, researchers designed and commissioned building of a simulated harsh environment with a pump and pipe skid. The design incorporated safety measures including a ladder and safety rails on the roof of the mini module (Figure 5 and Figure 6). The selection of the harsh environment locations were justified as reflecting work processes on actual ships which are highly demanding and dangerous due to exposures to heat, hazardous atmospheres, and uneven and obstructive work platforms due to extensive fixtures and fittings (Hossain, Nur, & Jaradat, 2016; Lee, 2013)

**Figure 5-Mini module with a pump & pipe skid (Photo)**

**Figure 6-Mini module with a pump & pipe skid (3D Model)**




*Source: AITI Photo Stock 2021*

### 2.2.1 Task (work order) development

The work order was developed to simulate practical tasks with transferability to small to medium enterprise (SME) participants and was designed in consultation with various shipbuilding and manufacturing practitioners. The work order was designed to include preparation to completion of a brief work process. Preparation steps included description of the work, work location, a list of personal protective equipment (PPE), tools, parts required and drawings. Execution steps included completion of a risk assessment and a set of task instructions, specifically:

- Task A: 2" blind installation
- Task B: pressure gauge installation
- Task C: valve closure

Each task had an objective quality evidence (OQE) requirement involving capturing images of completed work. Completion steps included text capture and work order submission. The same work order was used in different working environments and assigned a work order number:

- Work order A: Working at heights
- Work order B: Constrained space (inside the mini-module)
- Work order C: Confined spaces

The details of the work order are attached in Appendix A.

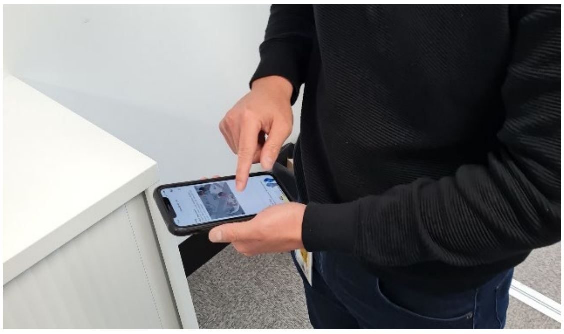
As this trial required participants to physically perform the tasks in harsh environments (i.e., tightening nuts and bolts), PPE was required including a high-visibility vest, steel cap boots, and safety gloves. Researchers endeavoured to source gloves compatible with navigating the phone screen, but gloves assessed in the market were inadequate for scrolling and tapping.

The trial compared AR glasses with a smart phone to assess the potential benefits of hands-free operation in a harsh environment simulated trial. There are various AR glasses available in the market, but ‘Google glasses Enterprise Edition 2’ (Figure 7) was chosen due to their light weight, flexibility and practicality. For the smart phone, iPhone XR (Figure 8) was selected because of its reputation and market penetration. Both devices have been widely used in digital work environments and significant benefits have been found in different industries.

**Figure 7- Person wearing glasses and display view**


*Source: AITI Photo Stock 2021*

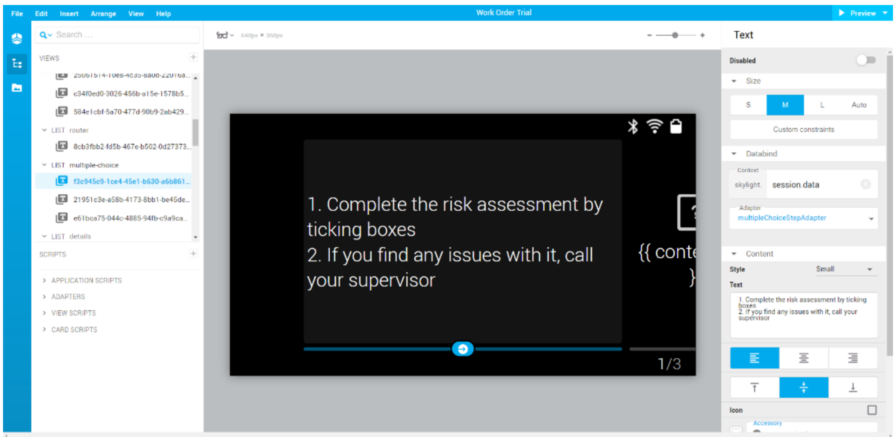
**Figure 8-Person working with phone**



*Source: AITI Photo Stock 2021*

Researchers chose the development software ‘Upskill Skylight’ to replicate the DWO to integrate with the phone and glasses. The software has an easy development kit providing various features including drag-and-drop user interface (UI) design and app templates for common use cases (Figure 9).

**Figure 9-Skylight app development page**



### 2.2.2 Task evaluation

Consistent with the holistic HFE approach underpinning the trial (see Section 1.1), the evaluation involved a mixed methods approach drawing on several different data sources (both quantitative and qualitative). Applying a variety of methods to tap different user perceptions and abilities allows a richer understanding of findings that aid in explaining, verifying, and contextualising the outcomes (Harrison, Reilly, & Creswell, 2020). Trial data drew on performance metrics, observations and users' feedback on their experience (for details see Section 3.1).

***Performance metrics***

These measures provide a quantitative output allowing statistical comparison between participants and locations. Criteria were selected based on key parameters of interest to the BAESMA R&T team and drew on standard survey items and methods where practicable.

- ***Usability***

Usability measures developed in consultation with BAESMA included ease of readability, ease of entry and retrieval of data, level of comfort, physical demands, and rating of device suitability for task. Each dimension was measured on a 21-point scale anchored at 0 (low) to 20 (high).

- ***Performance time (productivity)***

Performance time was measured from the time at which the participant commenced accessing the instructions in the work order. It included collecting specified tools, undertaking the risk assessment, accessing the workspace, undertaking the work as prescribed, collecting the OQE and submitting the completed work order. Performance time was measured in minutes.

- ***Productivity and quality (error)***

Performance was captured from the Skylight software using the Snagit 2020 app and analysed to count error occurrences. Errors included errors of omission (where a required action was overlooked) and commission, or an action error (where a mistake was made through an action) (Wilson & Sharples, 2015 p.796). Errors of omission included failure to tick boxes at the completion of key steps, and missing photo capture when OQE was required. Errors of commission included incorrect installation of components (non-compliance with work order quality requirements) and unintended exit of the work order. Error occurrences were measured in frequency counts.

- ***Observations***

Observational data were collected by monitoring participant behaviours throughout the entire trial period. Observations were independently documented by two researchers and included impressions of participant disposition, verbal commentary, visible behaviours, and problem-solving strategies. Observational data was text-based and qualitative in nature.

- ***User perceptions and feedback***

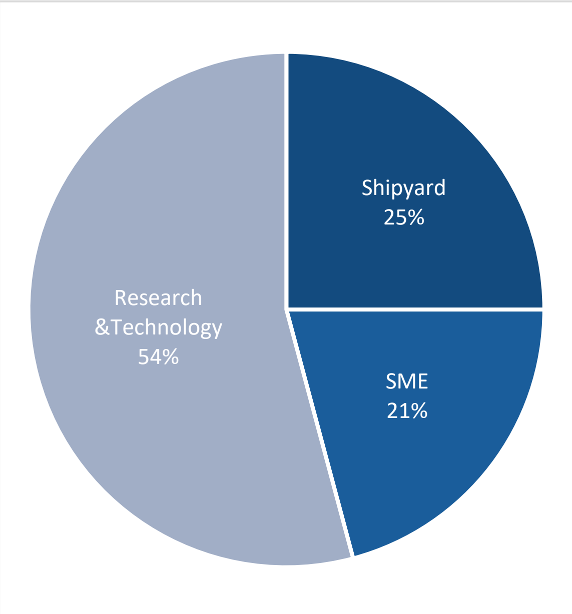
User perceptions and feedback were captured through the completion of an electronic survey at the end of each trial task. The surveys took about 10 minutes to complete and contained rating scales and free-text fields exploring participants' experience of the work task, environment and perceptions of the technology as it may apply to their work context.

### 2.2.3 Participants (end-users)

Twenty-four participants commenced the trial, after one withdrew before commencing the work order activities due to difficulties with the glasses[5]. Of the 24 participants completing the trial, two were females. Based on 13 responses, the average age was 38.6 years (standard deviation 12.6 years), ranging from 21 to 52 years. Two participants were left-handed equating to 8% of the sample[6].

All participants had some experience in the construction or manufacturing industries, with an average duration of 11.1 years (standard deviation 12.5 years), ranging between 1 and 35 years of experience. Participants represented three groups of workers associated with shipbuilding and manufacturing including workers from shipbuilding occupations, manufacturing workers from SMEs, and BAESMA Research & Technology employees (see Figure 10).

**Figure 10: Participants by employer group (n=24)**




All participants reported previous experience using smart phone technology in their personal and working lives. None of the participants had previous experience with any AR glasses, necessitating a familiarisation session in the use of the Google glasses before commencement of the trial.

[5] This participant was assigned the glasses as his first trial task but encountered significant difficulties in visually adapting to the glasses during the familiarisation session and opted not to proceed. Consequently, no trial data were collected for this participant.

[6] In this small sample, this is consistent with the best overall global prevalence estimate of 10% (Papadatou-Pastou et al., 2020)

# 3 Navigating the digital work order: Comparing technologies through performance and user experience

## 3.1 Performance outcomes

The trial assessed the utility of the phone and glasses in accessing a DWO to perform tasks using a pump and pipe skid in simulated shipbuilding harsh environments. Performance measures were derived using four data sources:

- a survey assessing usability indicators including rating scales and free text comments,
- time taken to complete each task,
- error counts, and
- researcher observations during performance.

### 3.1.1 Usability

Usability examined participant ratings of ease of reading, ease of information entry and retrieval, discomfort, physical demands, and device suitability for each device across three task environments. Descriptive statistics (where lower scores represent a more positive experience) are presented in Table 3. A sign test (see Appendix B) examined whether there is an increase or decrease in the median performance using the phone and the glasses, independent of order of presentation and location. Analysis revealed one statistically significant difference favouring the phone over the glasses for ease of reading the device, ($p < .05$)[7]. No reliable trend was identified for the other usability attributes, although results suggest the phone may offer a more positive experience overall.

The range values indicate wide variation in the spread of scores for each usability criterion.

**Mean vs Median**

The **mean** of a set of values is the sum of all the values divided by the number of values. This figure is most commonly referred to as the 'average' and is most frequently reported.

The **median** or midpoint is the middle value in a set of numbers. It is the value that separates the higher half of values from the lower half of values. The median is useful because it is not influenced by the presence of extremely large or small values and can provide a better understanding of a typical or common value in a data set.

Some statistical tests assess differences between mean scores and some compare median scores. Test selection is based on how the data are distributed (see Appendix B).

**Standard Deviation (SD)**

The SD reflects how spread out the data are from the mean. A lower SD indicates the data cluster around the mean; a higher SD shows the data are more dispersed from the mean (National Library of Medicine, n.d.). For any distribution, "about 95% of individuals will have values within 2 SDs of the mean" (Altman & Bland, 2005, p.903).

**Statistical Significance**

Statistical significance indicates that a relationship or result is unlikely to have occurred by chance. Significance levels (probability values) are normally set at:

- **p<.05** ('significant' – only 5% likelihood that the result occurred by chance) and
- **p<.01** ('very significant' – only 1% likelihood that the result occurred by chance).

It is important to recognise that as samples increase in size, so too does the chance that even very small differences between groups can become 'statistically significant'.

[7] Sign tests reveal that for ease of reading, 63% rated the phone more positively than the glasses, 25% rated the glasses more favourably than the phone, and 13% rated them equally for ease of reading information.

**Table 3- Comparison of performance metrics between devices**

| | Phone (n=24) | Glasses (n=24) |
|---|---|---|
| **Ease of reading information (Score 0-20 – lower score rated easier)*** | | |
| Mean | 5.7 | 8.7 |
| Median | 5.0 | 9.5 |
| SD | 5.6 | 4.7 |
| Range | 0-17 | 1-16 |
| **Ease of entering/retrieving information (Score 0-20 -lower score rated easier)** | | |
| Mean | 6.1 | 7.9 |
| Median | 4.5 | 7.5 |
| SD | 5.9 | 3.8 |
| Range | 0-20 | 1-16 |
| **Discomfort using the device (Score 0-20 – lower score more comfortable)** | | |
| Mean | 7.3 | 7.9 |
| Median | 5.0 | 5.0 |
| SD | 6.2 | 6.5 |
| Range | 0-19 | 0-19 |
| **Physical demands using the device (Score 0-20 – lower score less demanding)** | | |
| Mean | 6.4 | 6.4 |
| Median | 5.0 | 5.0 |
| SD | 5.6 | 3.7 |
| Range | 1-17 | 1-15 |
| **Device suitability for task (Score 0-20 – lower score rated more suitable)** | | |
| Mean | 5.7 | 7.4 |
| Median | 5.0 | 7.5 |
| SD | 4.4 | 4.6 |
| Range | 0-15 | 0-18 |

*Statistically significant sign test (see in text and Appendix B for details) *p<.05)*

A Kruskall-Wallis test (a non-parametric alternative to a one-way between groups analysis of variance) explored whether median scores were statistically significantly different between locations for ease of reading information[8]. Mean ranks showed that using the phone while working at height was rated easiest for reading (mean rank 8.1), with this significantly different compared to working in the simulated confined space (mean rank 16.8)[9]. One possible explanation for these differences may be the lighting conditions across locations. Task lighting was required for work inside and underneath the module in the simulated confined space due to darkness and the influence of shadows. As the phone was light-emitting, it is theorised that would be easier to read in poor lighting due to high levels of contrast (Teguar, 2019). Despite this, small sized screens and short viewing distances required by phone use, coupled with higher levels of work demand due to posture and effort, are likely to contribute to perceptions of decreased readability in poorer lighting conditions.

### 3.1.2 Performance time

Performance time refers to the duration required by each participant to complete the work order, commencing with collection of tools and parts, completion of a risk assessment, and ending with the digital submission of the completed work order. It excludes task briefing and the familiarisation time required for successful completion of the glasses task. Performance data were normally distributed, allowing the use of parametric statistics to compare mean differences.

Overall, participants took significantly longer to complete the work order, on average, using the glasses (mean=22.9 minutes) compared to the phone (mean=19.2 minutes)[10]. This difference in

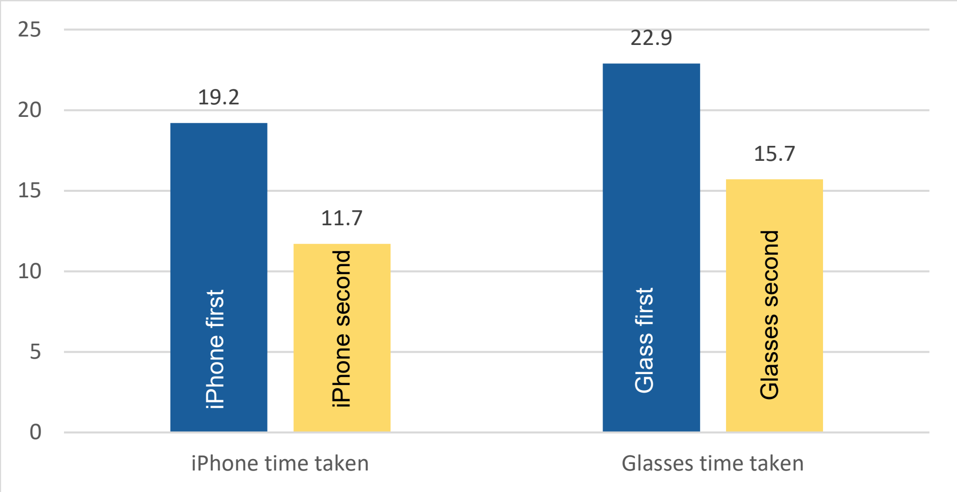
[8] Kruskall-Wallis test $X^2$ (2) = 6.32, $p$=.04. Post-hoc analysis with pairwise comparisons and Bonferroni correction: working at heights (8.06) and simulated confined space (16.88), $p$ = .036

[9] Although not statistically significant there was a trend suggesting an increase in difficulty in reading the phone inside the module (mean rank 12.6).

[10] Paired samples t-test: $t$ (23) =2.40, p<.05.

means is of medium magnitude or effect size (*d*=.45)[11]. However, as shown in Figure 11, there was a significant task learning effect. The time taken to complete the task on each device took significantly longer when using that device for the first time, meaning that using the phone first enabled participants to complete the subsequent glasses task faster[12].

**Figure 11- Task duration (minutes) by device type and order**




The size of the learning effect was medium[13] translating to a difference of 7.5 and 7.2 minutes respectively (see Table 3).

**Table 4- Comparison of time taken to complete task between devices**

| Device order | Phone time taken (mins) | Glasses time taken (mins) | Mean difference (mins) |
|---|---|---|---|
| **Phone first** | 19.2 (3.6) | 15.7 (3.4) | 3.4 |
| **Glasses first** | 11.7 (2.6) | 22.9 (4.1) | 11.2 |
| **Mean difference (mins)** | 7.5 | 7.2 | 7.8 |

[11] One way to aid interpretation of findings is to calculate the effect size which indicates the strength of a difference or association (the greater the effect size, the more likely the finding will be meaningful or of practical importance). When conducting a paired-samples t-test, Cohen's d is the most common measure of effect size. As a guide, .2=small effect; .5=medium effect; .8=large effect (Cohen, 1988). The *d* reported here is corrected for small samples but is best interpreted through comparison with other similar studies, where they exist (Bakker et al., 2019); see Appendix B for more information.

[12] A one-way ANOVA was conducted for each task mode – phone: $F(1,22)=34.0$, $p<.01$); glasses: $F(1,22)=22.4$, $p<.01$).

[13] Eta squared is the effect size reported with the use of ANOVA and is reported for each significant independent variable. The independent variable was device and the effect size associated with use of each device was eta squared (phone)=.61; eta squared (glasses)=.50).

The learning effect can be attributed largely to participants' existing familiarity with the functioning of the phone interface due to the ubiquitous nature of smart phone technology in daily life. The other influence on learning was the performance of the same task when using both devices. The same task was used to minimise the number of independent variables and avoid small sample sizes in groups; however, this conferred an advantage on performance time with the second device. This outcome may have been minimised by randomising the presentation of the three sub-tasks (blind flange installation, pressure gauge installation, and valve closure) and should be considered in designing subsequent trials.

### 3.1.3 Productivity and quality outcomes (error performance)

Productivity and quality outcomes were examined through counting errors during task performance. Participants were required to progress through the DWO following instructions and indicating completion of key steps by ticking a box icon in the top right corner of the device screen. Errors were classified into four categories including: box ticking missed, incorrect installation of components, photo taking for OQE missed, and unintended work order exit (see Table 5 for a summary). The largest category of errors was for 'box ticking missed' with higher numbers of errors experienced using the glasses. Most errors were made on the device used first, due to lack of familiarity with the work order. Error differences were attributed to lower visibility of the box icon due to smaller screen size of the glasses, with fewer box ticking errors made on the phone due to the icon being more salient than on the glasses. As indicated in user feedback, software design has a profound impact on the induction of these errors. For example, the work order on each device allowed the participant to progress through the task without ticking the box and there was no system design feature which warned of a missed step or prevented proceeding until the box was ticked. Also, a reduced number of errors was found with the later-used device due to the learning advantage conferred by completing the task the first time.

**Table 5 - Error identified during trials**

| Start Device | Box ticking missed | | Incorrect installation | | Photo taking missed | | Work order exited | |
|---|---|---|---|---|---|---|---|---|
| | Phone | Glasses | Phone | Glasses | Phone | Glasses | Phone | Glasses |
| Phone First | 28 | 24 | 3 | 4 | 1 | 0 | 0 | 9 |
| Glass First | 5 | 36 | 8 | 6 | 1 | 1 | 0 | 8 |
| Total | **33** | **60** | **11** | **10** | **2** | **1** | **0** | **17** |

Many participants experienced unintentional exiting of the DWO due to a lack of familiarisation with the glasses and their sensitivity to unintentional voice and touch activation. Software did not request confirmation of exiting a work order. In addition, when using voice commands, many participants were unfamiliar with the specific phrases that constituted commands. For instance, they said "navigate right" instead of "scroll right", and "taking a picture" instead of "capture photo". Also, network errors were a critical factor that occurred unexpectedly when executing tasks. One quarter (n=6) of participants experienced network errors (internet disconnection) during trials which exited them from a work order and extended task execution times.

Many participants struggled to clearly see the work instruction due to the very small size of the glasses display. It led to incorrect installation of components and missed photos for OQE activities. In addition, some participants collected incorrect materials or tools resulting in poor quality of physical task completion. Even though participants wanted more detailed instruction, the small size screen limited the amount and detail of information that could be accommodated by the glasses.

Errors of omission with either device could be reduced through improved software design, preventing participants from progressing through the work order until the required checks are completed. Increased size and conspicuousness of tick boxes would also reduce such errors. Errors of commission could be reduced through more effective interface design and use of verbal commands and touch gestures consistent with user expectations and aligning with similar technologies. Software interfaces require extensive testing to assess usability and error behaviours with a range of representative end users.

### 3.1.4 Observations – safety and strategies

Observations of task performance were recorded noting participants' behaviours and commentary, with the purpose of identifying performance strategies and safety implications.

***Phone – safety and strategies***

One of the most salient safety issues arising from phone use was the incompatibility of gloves with the screen, inhibiting scrolling and typing and leading to frequent removal and reapplication of gloves. One participant was observed to roll up his sleeves and attempt to use his elbows to scroll the screen. Another stated: '*it's insane every time you need to take off the gloves'.* While incompatibility of gloves is a significant usability issue, the need to use gloves is a safety requirement to reduce the risk of hand injuries. Constant removal and reapplication of gloves to interact with the phone have clear safety consequences as well as increasing frustration and reducing productivity.

Several participants had difficulty with carrying a phone while moving and climbing. Although participants were provided with a tool bag, there was reluctance to place the phone inside due to concern it may be damaged. Many participants placed it in pockets, with one observed to have three phones in one pocket while climbing the ladder to the roof of the module. Female participants commented that the pockets on their uniforms are not suitable for carrying phones. This observation stimulated a lengthy discussion on the design inadequacies of women's work pants, which do not fit well and are not comfortable. Poor fitting clothing has direct impacts on safety when working in active jobs in confined or restricted spaces, impeding movement and comfort. These observations, supported by qualitative survey feedback emphasise the need for lanyards, pouches or pockets for securing phones during movement.

A common strategy adopted to facilitate work performance using the phone included verbalising instructions while reading. This strategy was used as a way of mentally checking off tools, parts and instructions as an aid to memory, adopted by many participants using both phone and glasses. To minimise the application and removal of gloves, strategies included partial removal of gloves to use thumbs only to scroll and type. One participant forgot to bring his prescription glasses so used the phone in landscape to enlarge text. A common problem with the phone was the need to repeatedly pick it up and place it down. Strategies to minimise the risk of damage were to place it on the tool trolley, beneath the pump and pipe skid or on the cavity wall in the simulated confined space. These locations minimised the risk of the phone being stood on or struck with tools.

***Glasses – safety and strategies***

Most safety issues arising from the use of glasses were visual in nature. Several participants were observed to squint, read with one eye closed to improve focus, or compensating with awkward body postures to improve the visual field, for example constantly looking up or bending their neck or trunk.[14] On observing one participant's awkward neck postures, frequent efforts to reposition the glasses, and pauses, he commented 'it's out of focus, that's all'. Many participants commented on the sensation of fatigued or strained eyes and the greater risk of this when glasses are used over longer periods.

Related to visual discomfort, several participants reported reduced awareness of their environment while wearing the glasses, a phenomenon referred to in human factors as situation awareness. One participant commented on not liking the glasses because 'they feel isolating and cut down broader awareness of the environment'. The trial glasses had the viewing pane positioned over the right eye and several participants were observed squinting and closing the left eye as a strategy to help focus their view. Another participant reported experiencing a double image and needing to close the left eye, often 'losing spatial awareness' One participant experienced the glasses 'going to sleep' and reported 'this is good, it doesn't distract the sight'. Another participant offered 'there's lots of manoeuvring around a sub[marine], I would not want to have to move around wearing the glasses in case of tripping'. One participant stated, 'the glasses could slip off the face when working at height or in a confined space'. Reduced situation awareness and distraction are significant safety considerations with implications for errors of judgement leading to slips, trips, falls and collisions.

Strategies to facilitate performance during glasses use included taking time to adjust the glasses for best fit and alignment before commencing work and compensating for visual difficulties by closing the left eye to improve focus during task performance. Several participants were observed to move their heads to position the glasses' in-built camera to capture the field of view when taking photos of OQE.

Like using the phone, many participants tended to verbalise the instructions they were viewing as they progressed through the work order. This strategy aided the user by reinforcing the instructions. Unlike the phone, researchers were able to view a projection of the information the glasses presented to the participant, so were more aware of error behaviours as they occurred. Other strategies were the choice of interaction method either voice or gestures. Most participants used a combination of both voice and gesture, depending on what felt more intuitive to the individual for completing each required action. Once they had learned the key phrases, most favoured voice commands, although others reported 'feeling weird' or self-conscious using voice commands and opted for gestures. A common error was the failure to check off each stage of the work order by ticking a box icon. One participant commented that they chose not to do so because they wanted to refer to the steps later. The box ticking requirement highlights several interface design issues about how a user knows where they are in the work flow, and having features that prevent progress without completing key steps. Check boxes also needed to be made more salient to prevent being overlooked.

Strategies for use had implications for successful task performance and safety outcomes. Many strategies were adopted to overcome less satisfactory usability issues with each device. The key usability issues targeted by strategies were the handling of the phone and use of gloves, while for the glasses, visual acuity and comfort, and situation awareness were most salient.

[14] It is noteworthy that persons with vision problems requiring glasses were excluded from the current trial.

## 3.2 User perceptions and feedback

### 3.2.1 Device suitability

***Phone***

Many people mentioned that the phone has great potential in industrial environments, it has a high level of familiarity and thus can make practical tasks more intuitive in providing a clear reference point, as explained by one participant:

> *I don't have to worry about what to do because I can see all I need for a task*

Although the device was ruggedised, participants felt it was not durable enough saying the 'device is fragile', although they believed that phone would be a very suitable platform in the future evolution of the DWO.

***Glasses***

The glasses can be operated by touchpad or voice recognition. Participants indicated that the voice recognition was useful due to its hands-free capability. Participants explained the value of the glasses in limiting the hand and body movements required to manipulate a paper work order and drawing, stating:

> *The glasses had a low impact on the range of movement required, they were easy to use.*

> *I didn't even attempt swiping at all with my hands once I started using the voice.*

> *Glasses were physically comfortable to wear and did not hinder normal movement or activity.*

However, some participants did not use the voice recognition because gesture navigation was consistent with the natural use of familiar interactive technology devices. Also, continuous voice commands were not desirable due to various factors including noisy environments, working closely with other colleagues on site or privacy. Many participants emphasised that glasses could be suitable for more active and complex tasks such as cable harnessing. Other advantages were having a clear understanding of task context and progress throughout completion of the work order, with participants stating:

> *It was great to look at next steps whilst still completing previous step.*

> *Once adjusted to the interface I found workflow was improved.*

Positioning of the glasses was a critical factor in successful use. Continuous movement of the head and body altered the location of the glasses and display, resulting in needing to move or hold the glasses to focus the screen clearly, as described in this comment:

> *I noticed glasses moved on my face when gesturing with finger was done, had to keep moving them back into place.*

Several participants commented on the technical capabilities of the glasses. Although image capture was effective, the camera did not have a flash and its focus was not able to provide clear definition of detailed data.

Participant assessment of phone suitability was most influenced by its familiarity and ability to present a work order clearly, though it was limited by a perceived lack of durability. For the glasses, device suitability was most influenced by the ability to work hands-free, though it was limited by positioning and alignment to enable comfortable viewing of information.
Device suitability was also limited by technical features for image capture.

Successful use of both phone and glasses required network and internet stability as critical factors for continuity in the use of real-time data.

### 3.2.2 Comfort and ease of use

***Phone***

The phone provided various features including small size, good readability and familiarity with operation. Participants highlighted the usefulness of the camera for capturing data immediately following task completion. One participant liked using the DWO with the phone, noting reduced effort involved in handling and marking up paperwork:

> *This was more like a paper work order but I could submit it at the end and walk away without processing paper forms.*

Most participants highlighted the need to repeatedly remove gloves to use the phone suggesting that having compatible safety gloves with any device is critical. Although some participants used compatible gloves, they still had difficulty pressing icons to activate the screen. An undesirable consequence was that participants forgot to wear gloves during task execution, as highlighted by one participant:

> *Touch screen use led to forgetting gloves, as they would likely render the screen unusable.*

For practical applications in the shipyard, different gloves are required to match specific tasks and risks. Participants highlighted that welders require heavy-protective gloves as opposed to electricians who wear rubber-insulated gloves. Participants expressed concern about carrying and securing the phone throughout task completion, with implications for use throughout a working day. For example, participants had to put the phone in and out of a pocket when climbing ladders or when performing tasks requiring both hands, as reflected in the comments:

> *The phone was very inconvenient to use while working on tasks compared to glasses.*

> *The phone was hard to carry around when carrying tools and would be difficult to use in the dark or at sea.*

Participants suggested having a lanyard or attaching the phone to arms or legs (with Velcro) to make it more secure and visible during task performance. Also, placing the phone in locations where it was safe from crushing, impact or being stepped on was a challenge, especially when working in more restricted harsh environments. Holding or carrying the phone presented an additional risk factor when carrying tools and parts, particularly when negotiating heights or restricted spaces.

***Glasses***

The glasses weighed only 46 grams and can be tailored to individual users through fitting of prescription lenses. Most participants were impressed by these features and felt comfortable to use the glasses while executing tasks. However, using the glasses effectively requires time to carefully adjust the fit and alignment to ensure the display is in full view. Many participants found the display of the glasses too small, requiring a high level of concentration to read text, thus increasing discomfort and eye strain as highlighted in the comments:

> *This seems uncomfortable for long usage. It is really hard to focus on a small screen and sometimes I was unable to see some description on the display.*

> *It felt like a task navigating the instruction and took focus away from the task and placed it more in the use of the glasses.*

The amount of information that can be displayed on one screen was extremely limited, requiring information to be divided into multiple slides within the screen, even for a simple task. Additional slides required participants to make more scrolling actions to progress through the work order, as highlighted in the comments:

> *I had to scroll between a lot of screens.*

> *I would prefer to use glasses only for referencing not a step-by-step process.*

In summary, for phone use, comfort was most influenced by the need to repeatedly remove gloves to interact with the phone, and difficulty securing it between micro uses (requiring constant placing and picking up). The key comfort and ease of use factors for glasses involved visual performance relating to correct alignment, eye fatigue and adequate resolution of images.

### 3.2.3 Readability

***Phone***

The phone provided a suitable size of display and participants reported the phone had better readability than the glasses for the trial task. Screen brightness was adequate, making reading instructions easier, however, some participants commented that the relatively small screen required them to continually pause and pick up the phone for most uses. Participants suggested:

> *This is still small… and would be very suitable in iPad form.*

> *Text is small, must hold device up to face to read.*

Usability and user interface issues were considered a critical factor that could prevent participants from seeing all the information on the screen. Several suggestions were made for improvements:

> *Bullet point or animation would be more beneficial.*

> *Some indication of progress would be useful.*

> *Information provided was good but there were user interface issues preventing me from seeing all of the images.*

***Glasses***

Readability with the glasses was affected by the contrast between the screen brightness, viewing background and natural light that varied depending on working conditions. Working in the confined space (below the mini module) and inside the mini module were darker environments that required supplementary task lighting. In contrast, the working at height condition on top of the mini module had greater natural light and participants rated readability there as easier. One participant working in the confined space condition commented:

> *I found myself searching for a blank wall to look at so I could see the projection.*

Most people highlighted the importance of a well-designed user interface to improve the readability of screens. For instance, one of the steps in the work order showed a list of parts to be collected, but the part list was presented as a block of text. One participant explained:

> *It would've been better if the part list was shown with bullet points or a clear table including check boxes so that users can clearly see which parts are needed.*

Participants liked the functionality of the glasses in that they were not required to look elsewhere for essential information. However, the scale and resolution of the images made the glasses less helpful when needed, as reported by this participant:

> *I found reading the images more difficult and probably not enough detail to inform me.*

Participants overall reported readability more favourably with the phone although some difficulties were encountered with small text size and the design of the graphical interface. For the glasses, readability was most influenced by the small size of the screen, contrast factors and design of the graphical user interface. Readability emphasises the importance of the interaction between hardware and the graphical user interface as the medium for information presentation. These factors are interdependent and highlight the value of assessing usability of software and hardware in achieving high levels of user acceptance, satisfaction, and performance.

## 3.3 Learning effects

### 3.3.1 Phone

Most participants were highly familiar with smart phones, particularly the Apple iPhone, as this technology has long been prevalent in modern society. This high level of familiarity produced a level of comfort with expectancies for functionality and reduced the learning effort on participants.

> *Phone was very normal in use and easier to navigate.*

> *This was much easier than the glasses.*

### 3.3.2 Glasses

None of participants had prior experience with the Google glasses specifically or AR glasses in practice. Despite participating in a familiarisation session, most participants were not confident using the glasses.

> *I need some time to familiarise with the glasses. I wasn't sure what gesture was needed to navigate the device like submitting the photo for example. Also, remembering all the commands was annoying, caused errors with navigation.*

## 3.4 Result summary and implications for adoption

Some participants approached the trial with a preconception the glasses would not provide practical value for improving work in harsh shipbuilding environments. Several participants reported being impressed by their capability after their trial.

> *Prior to using them, I felt the practical applications would be very limited, but after using them saw more areas for use and I can see the potential with some fine tuning.*

> *This definitely has potential. I was overall impressed.*

This trial has demonstrated the utility of the phone and glasses in accessing a DWO in harsh environments emphasising ease of use and safety. The results support some of the benefits DWO are expected to bring manufacturing businesses (see Section 1.2), while highlighting barriers requiring attention to achieve successful adoption. Overall participants slightly favoured the phone as the preferred device (as borne out in both qualitative and quantitative feedback) though preferences were mixed. The trial examined a simple digital workflow in simulated harsh environments of relatively short duration (approximately 20 minutes) and outcomes may have intensified and increased discomfort if the task was extended (e.g. eye fatigue). Key HFE strategies to assist in translating the trial outcomes to real world industrial environments include:

- **Undertaking a glove trial**
  Usability of the phone was significantly impaired by incompatibility of safety gloves that must be worn in harsh environments. Constant removal and reapplication of gloves led to failure to use them through forgetting, or non-compliant use where gloves were partially removed to allow scrolling with thumbs. To ensure the successful uptake of the phone, it is necessary to identify suitable gloves that will allow scrolling and tapping. An alternative option could be to assess the feasibility of using a tethered and magnetic stylus to activate hand-held device screens.
- **Addressing manual handling implications**
  The need to constantly handle the phone, picking it up and placing it down led not only to frustration but had practical implications for increased safety risks. Carrying the phone was problematic when carrying tools and parts, especially when accessing confined and at height workspaces. Phones require attachments like lanyards or Velcro, or pouches in tool bags to facilitate safe carriage.
- **Visual testing and fitting**
  Glasses require careful fitting and alignment to ensure acuity in the visual field, avoidance of unnatural flexed or extended postures, and compatibility with other PPE, including hard hats and hearing protection. Many older workers experience presbyopia – an age-related difficulty in focusing on near objects (Katz et al., 2021). Adoption of AR glasses in the shipyard will require testing and fitting, including the possibility of prescription lenses, to ensure optimal visual performance that limits the risk of eyestrain and fatigue.
- **Training on specific technology**
  The glasses were novel for most trial participants who needed to learn gesturing and commands to enable effective use. For broader adoption in the shipyard, specific training is required to support users to learn verbal commands and gestures to access the full functionality of the glasses.
- **Matching device to location, task and individual**
  No one device will be ideal in all situations, therefore devices need to be matched to location, task and individual characteristics to promote effective use. The glasses were reported to reduce situation awareness, so are less desirable for use at height. The complexity and duration of task also influences the effectiveness of the glasses. Due to small screen size, presentation of more complex information is limited as it requires multiple screens and increases the need for scrolling and eye fatigue.
- **Usability testing on presentation of the DWO**
  Before implementation of a DWO, its usability should be assessed with a representative sample of end users to ensure compliance with usability principles (Brooke, 1996). Performance and design are interdependent, with design factors contributing 50% to 90% of variation in overall performance (Smith, 1994). The seamless integration of hardware and software is critical for optimal usability and ensuring a product is easy and comfortable to use. This involves compliance with standards for text size, layout, colour contrast and commands.
- **Connectivity**
  The successful implementation of digital technology in harsh environments is limited by the adequacy and reliability of the network. Connectivity is essential for transfer and speed of access to information. Connectivity at Line Zero during this trial suffered occasional drop-outs, hindering user performance. However, both phone and glasses technology can be used offline, offsetting connectivity limitations for brief periods of use.

# 4 Accelerating the uptake of digital technologies in industry

## 4.1 Drivers for change

Accelerating the uptake and diffusion of digital technologies in manufacturing requires significant organisational change within enterprises and along the supply chain. Digital technologies are rapidly changing how products and processes are designed and serviced, leading to fundamental shifts in strategic focus and the design of work (Savastano, Amendola, Bellini, & D'Ascenzo, 2019). Such disruption inevitably impacts on individual and collective behaviour in response to change (Atkins et al., 2017). The effectiveness of technology adoption is influenced by knowledge, skills, identity (early adopter versus risk averse), beliefs about the capability for change and the consequences change brings. Motivation and goals are influenced by social acceptance and emotional factors that can reinforce or undermine the change process (Atkins et al., 2017). People are inherently resistant to change due to fear of losing something of value, the uncertainty a new future state brings, or low tolerance for change (Wentworth, Behson, & Kelley, 2020). To achieve the desired shift in behaviour and create a new future state, drivers for change must be promoted and barriers identified and mitigated.

In tandem with this DWO trial, a survey[15] was conducted with a sample of shipyard workers (n=211). The participants were 90% males, average age 39.5 years (range 17-71 years), with average 10.2 years (range 0-50 years) of manufacturing experience. Several drivers for change were identified from this group including:

- they performed work that requires a high level of collaboration with others (91% agree to some extent, while 50% strongly agree), which makes work amenable to digital work management
- they experienced difficulties accessing information easily, sharing information across teams and completing work efficiently (around 30% disagreed to some extent that current practices achieved these outcomes easily), and
- workflow interruptions were common, with around 40% experiencing schedules changing, delays or need for additional checks most of the time, or always.

In terms of workforce readiness for technology adoption, survey participants reported:

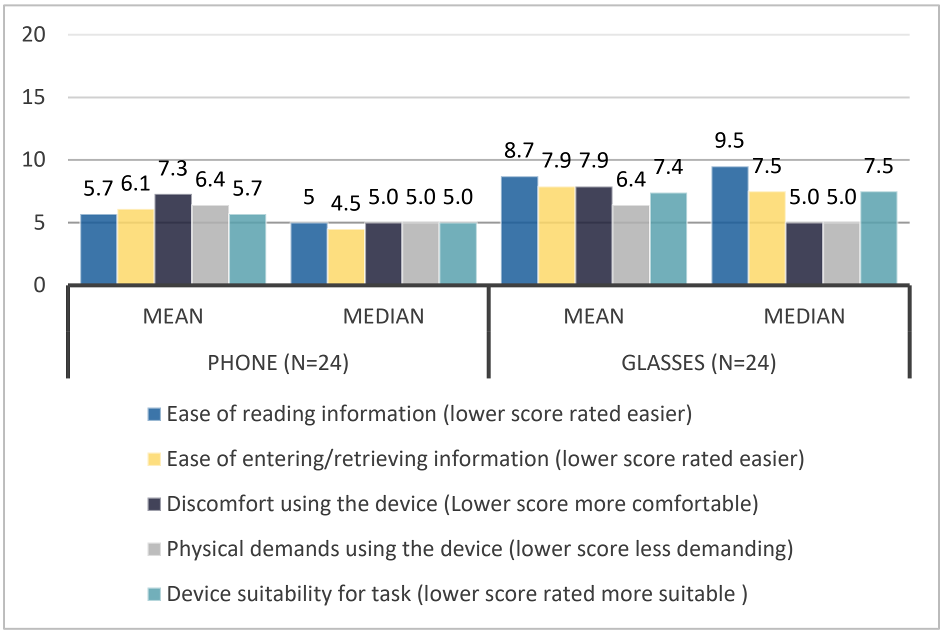
- positive attitudes to technology, with 50% agreeing to some extent that they keep up with the latest technology developments
- confidence that DWO would be useful, with around 70% reporting a belief that DWO would provide opportunities for skill development, improve efficiency and enable easy record keeping, and
- an expectation that DWO would be easy to use, with 64% agreeing or strongly agreeing they would use DWO if they had access to them.

The benefits attributed to adopting DWO as a significant step towards digital transformation were summarised in Section 1.2. The smart phone and AR glasses are enabling technologies that support successful adoption of DWO in industrial environments. The benefits associated with AR glasses in digital working environments were summarised in Table 1 (Section 1.3.3). DWO have potential to enable business improvement through greater efficiency, easier traceability, reduction in error rates and greater accuracy (Riege, 2005). Cost is a main driver for moving from

[15] Flinders University Human Research Ethics Committee Approval Number 2670

paper-based to digital work that enables organisations to reduce administration time and deliver a higher quality product (Saunders, 2019). For organisations, broader potential drivers for adoption of DWO include improved management and visibility of the process, vertical and horizontal integration of work practices, processes and data, and increased agility to respond to customer demands. For individuals, DWO present opportunities for more efficient work practices, access to timely information and associated improvements in work satisfaction (Mourtzis, Xanthi, & Zogopoulos, 2019). Results of the usability trial are summarised in Figure 12.

**Figure 12: Summary of trial findings phone versus glasses**




The potential benefits for productivity and efficiency in using a DWO were not fully assessed in this trial as there was no comparison with current practices involving paper-based processes. Participants anticipated a benefit from using technology to access a DWO, commenting:

> *[DWO] definitely has potential. I was overall impressed, and I thought that using a device made the task more intuitive.*
>
> *All the information is there without the need for printouts/hardcopies of the workorder or drawings - very easy addition to the workflow.*
>
> *This was more like a paperwork order but I could submit it at the end and walk away without processing paper forms.*

Performance times favoured use of the phone due to its familiarity but participants found the glasses effective and felt use would become more intuitive with training and practice. The potential for greater access to real-time information and communication with co-workers was also seen as valuable:

> *New technology was great, took a little getting used to. Can see the benefits of on hand information.*
>
> *The ability to live share with supervisors and managers or other tradesmen is wonderful. Jobsites are an ever-changing place and having quick, easy handy access to information is critical.*

The trial indicated there is an appetite for further investigation of DWO and different devices for accessing them in different environments. Despite an overall positive response to the potential for using a DWO, findings of this trial emphasise the choice of device is critical to ensure optimal usability and must be matched to use cases. In this trial, harsh environments were assessed as a particular use case where minimising items to be carried was a key usability factor. The digital devices had value in being small, enabling hands-free use (with some modifications to the phone) and providing real time access to information and communication. Findings highlight aspects of implementation that require further analysis to strengthen drivers for change and accelerate acceptance by users and uptake by industry.

## 4.2 Barriers to change

Barriers are powerful forces in hindering behaviour change. Technology providers, industry leaders and researchers working in partnership can help minimise barriers by building optimism in industry that technology adoption will be successful.

### 4.2.1 Limited applications and use cases

Limiting forces in the uptake of AR technology have been the lack of identified use cases and supporting case studies to demonstrate benefits (Koelle et al., 2017). In shipbuilding, applications using AR have been developed in pipe layout planning (Olbrich, Wuest, Riess, & Bockholt, 2011) to assess, check and edit drawings prior to manufacture and installation. Other potential applications in shipbuilding and manufacturing include checking layout and guiding installation of electrical wiring and other components during fit out, and assembly of electrical harnesses. The AR glasses used in this trial are cost effective ranging from AUD $2000 to AUD $3000 with potential of saving time and errors in fabrication and assembly. Other limiting factors of AR technology have been poor ergonomics, comfort, and usability where interfaces have been awkward to manipulate (Koelle et al., 2017). Possible applications are dependent on technological specifications and the capacity of potential end-users to identify candidate applications and opportunities.

**Recommendation 1**: Business cases are needed which incorporate business opportunities and the HFE impacts of the workforce undertaking ‘demanding, dirty and dangerous’ work. Cost benefit should also include the savings related to improved productivity, reduced administration costs and the prevention or minimisation of injury, absenteeism, and dissatisfaction

**Recommendation 2**: Business cases can be informed through conduct of technology trials in situ in collaboration with researchers, industry leaders and associations, and SMEs to share knowledge related to technology, HFE, business development and change management.

### 4.2.2 Harsh work environments

This trial focused on harsh environments simulated in a mini-module. Workers in real-world harsh environments are exposed to dust, noise, fumes, moisture, and extreme thermal conditions (Lee, 2013). Work takes place on uneven, constricted work platforms inducing awkward postures that increase the demands of highly physical manual tasks. These work environment features could not be simulated and therefore broader usability issues could not be assessed and were beyond scope. Benefits of portable digital devices include their small size and potential for hands-free use. Findings of this trial emphasise several shortcomings of the phone in terms of the need for compatible gloves and fastenings to secure it to the body during use. For the glasses the limitations were largely visual in nature and there were potential issues for reduced situation awareness. These issues relate to usability and can be addressed through attention to correct fitting and matching to task. Other environmental factors not considered in this trial are likely to have significant impact on successful adoption and include durability, reliability and connectivity in harsh environments.

**Recommendation 3**: Real world trials are required to assess aspects of usability in harsh environments. Portable digital devices for use in harsh environments require ruggedised cases (for phone) and storage pouches for when not in use. Suitable storage and fastening methods need to be designed in consultation with end-users to enhance usability. Different methods of activation (voice, gestures, touch) are required to provide alternatives (e.g. to voice activation) in noisy environments and in situations where hands-free use is required due to task demands. Suitable gloves should be trialled to ensure compatibility with touch screen activation. Devices should be trialled in the actual physical environment to assess durability, reliability, and connectivity. Battery life should also be considered as a factor in usability in real world trials.

**Recommendation 4:** Additional AR technologies should be trialled in harsh environments to overcome some of the limitations with the Google glasses. Realware and Zebra AR are potential candidates. Realware AR has ruggedised features and incorporates safety glasses and is compatible with hearing protection and hard hats so would be potentially more suited to harsh environments. Zebra AR can be connected to an Android smartphone that provides more flexibility within an organisation's total ecosystem so would be more suited to larger organisations requiring a high level of integration.

### 4.2.3 Usability of devices

Usability of devices is dependent on effective design that supports patterns of use consistent with user expectations and experience. Effective design integrates features of the software and hardware as an operational unit. Contrast is a critical usability feature for phone use but especially for AR where images and text are projected onto the field of view. Text is generally easier to read with dark font on a light background, however text presentation in AR glasses has found to be more readable if presented as white text on a black billboard (Klose et al., 2019). Layout and use of icons are also critical features of software design. Text is more easily read if presented in lines rather than blocks and consistent spatial relationships and navigational cues are used throughout screens and functions. A minimal size font of 9 point and optimal size of 30 point are recommended for AR displays (Klose et al., 2019). Information on an AR projection should be able to be turned off easily by the user in hazardous or time critical environments to prevent distraction in overload situations.

Several interaction modalities (e.g. touch, gestures, voice) provide flexibility for use in harsh environments where noise, hands-free work or high levels of concentration are required. Design of actions need to be consistent, including touch conventions (e.g. double tapping, pinching and dragging to enlarge image) and voice commands. Consistency in these features enhances rapid learnability and aligns with users' expectations from similar devices on the market. User testing is recommended for designing voice commands in specific work locations.

For wearable AR interfaces, the field of view is limited by human gaze which is a combination of body position and head and eye orientation, creating a range of +/- 55 degrees (Melzer, 2017). The field of view needs to be kept as small as possible to minimise eye strain and ensure stable balance, while achieving task performance. Field of view is of greater importance in visually degraded environments such as darkness (Melzer, 2017), an issue common in confined spaces.

**Recommendation 5**: Portable digital device and software manufacturers working with representative end-users must design features of devices and software to ensure ease of use. Devices and software should comply with usability standards such as ISO 9241:2018 *Ergonomics of human-system interaction* and design usability heuristics (e.g. (Endsley et al., 2017) specific heuristics for AR). Key principles include:

- fit with user environment and task,
- form communicates function,
- minimise distraction and overload,
- adaptation to user position and motion,
- alignment of physical and virtual worlds,
- fit with users' physical and perceptual abilities,
- accessibility of off-screen objects, and
- account for hardware capabilities to achieve optimal integration.

### 4.2.4 Implications for implementation

***User support***

DWO and portable digital technologies are proclaimed as being time efficient to use. However, this goal is more likely to be realised with adequate instruction, training and supervision of the workforce during the introduction of technology. The use of portable technology requires procedures for allocation, checking in and out, hygiene, maintenance and servicing to ensure devices are ready for use when required. In the case of AR wearable technology such as Google glasses, correct fitting is required for effective use. Age-related presbyopia (a visual impairment in near sight) is common in people above the age of 45 years with prevalence in North America estimated at 80% by age 55 years. Around 16% of affected people do not have corrected vision (Zebardast, Friedman, & Vitale, 2017). Many participants in the trial reported visual strain during the brief period of use of the Google glasses but were not aware of any visual impairments. Long term AR users should have a vision assessment and be test fitted for optimal use.

Work in manufacturing environments is often hazardous and requires use of PPE. AR technology must be integrated with PPE, including hearing, eye and head protection in harsh environments. User trials are recommended before procurement of AR technology to ensure integration with safety requirements.

**Recommendation 6**: The workforce must receive adequate instruction, training, and supervision during the introduction of new technology. Successful introduction requires procedures for device allocation, checking in and out, hygiene, maintenance, and servicing of devices. Users of AR technology should have a vision assessment, and be individually fitted for devices. AR technology must be trialled to ensure compatibility with standard PPE used in manufacturing environments.

***Change management***

Change management deals with people-focused issues, including behaviours and perceptions that can help or hinder achieving the desired goal. Successful change management requires overcoming fear and uncertainty by responding to emotions, adopting a planned approach in which the vision is conveyed to the workforce, ensuring they are empowered to act on the vision, establishing short term goals, building on improvements, and embedding and sustaining new approaches (Wentworth et al., 2020).

Cultural factors are highly influential in effective change management. Supportive cultures will encourage workers to try technology, to learn and to adapt to new practices (e.g., wearing new technology or using gestures or voice commands in the presence of co-workers), where resistant cultures may spread fear and undermine change. Resistance may surface where the workforce does not understand the need for, and scope of change, creating fertile ground for distrust.

Participants in the shipyard survey run in parallel with this trial identified concerns about DWO and their use, reporting:

- Expectations that face-to-face interactions would be reduced, with 32% extremely or to a large extent concerned, and
- Perceptions that confidentiality of information would not be maintained, or that workers would be monitored closely, with 26% extremely or to a large extent concerned.

Fear and uncertainty about the potential for surveillance, how the wealth of information collected may be used, and impacts on social interaction are common concerns arising from the introduction of digital workflows (Caruso, 2018). Implementing new technology is a business investment and for success and sustainability requires an equal investment in bringing the workforce along on the journey. Fundamental to success is engaging the workforce early in the need for change, promoting a vision, encouraging dialogue, and responding sensitively and promptly to concerns. Planning a strategy and engagement process for technology adoption, along with encouraging user involvement in testing, trialling and design of policies, procedures and training, will enhance acceptance.

**Recommendation *7:*** Organisations and leaders require a greater understanding of the principles and practices involved in effective change management. Key principles include:

- Clearly articulate the reasons for change and promote a vision
- Communicate key information, share information often and involve workers in the process
- Listen carefully and respond sensitively to worker's feelings and concerns
- Provide training, both technical (e.g., DWO content and process, AR gestures and commands), and individual development (e.g. opportunities to acquire new skills) and allow time for workers to trial and learn the technology without expecting rapid high productivity
- Seek ongoing feedback from the workforce throughout change to identify and address any unexpected issues early.

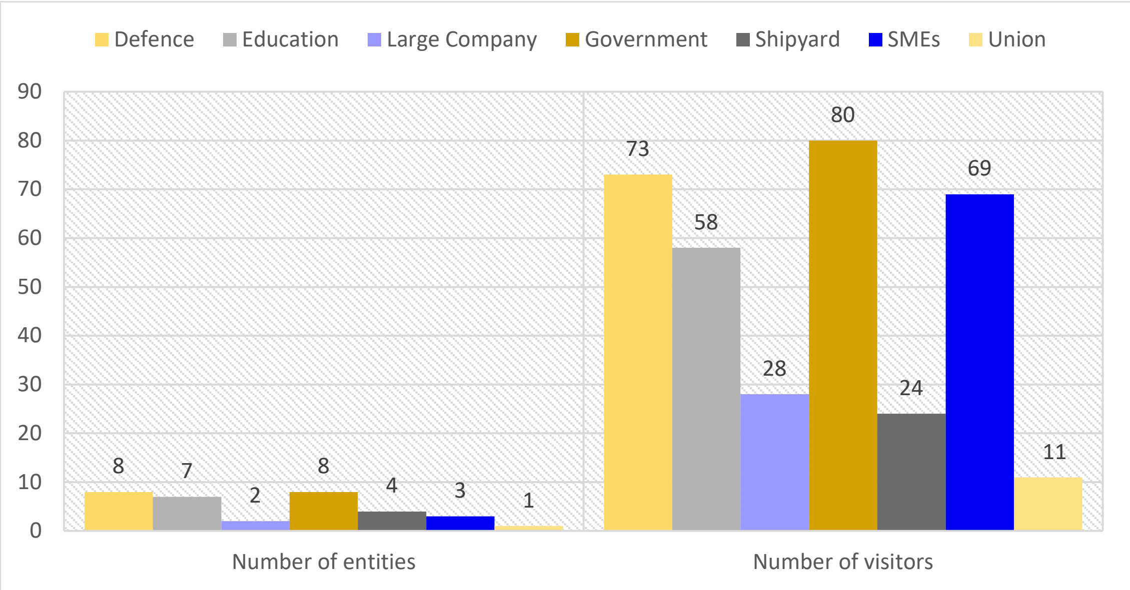
### 4.2.5 Education and awareness raising

Government, business, industry leaders and associations, technology providers and researchers can all play a pivotal role as trusted advisors in educating others on the potential and pitfalls of investment in new technology. Having opportunities to learn from others who have embarked on a technology journey promotes interest and confidence that technology solutions may help realise business growth and development goals. At the Tonsley

Innovation District, Line Zero and the Pilot Factory of the Future provide opportunities to test technology in a small-scale and low-risk environment. Visitors to the Pilot Factory of the Future have been introduced to HFE and viewed demonstrations, or experienced AR and other technologies. A summary of visitors (and the industries represented) to the AR technology demonstration between February and April 2021 is provided in Figure 13.

> **Recommendation 8:** Government, industry leaders and associations, technology providers and researchers can play a key role in educating and raising awareness of the potential and pitfalls of new technology. Development of collaborative centres, such as Line Zero Pilot Factory of the Future in which small to medium enterprises can trial technology on identified applications from their own businesses provides opportunity for active learning and confidence to translate to implementation, accelerating the uptake and diffusion of technology. An important starting point is for enterprises to optimise existing processes first by auditing to ensure they add value. Matching the technology to processes, people and contexts is the next step for delivering efficiencies.

**Figure 13: Visitor traffic to Pilot Factory of the Future**



# 5 Conclusions and future directions

This trial demonstrated the application of portable digital technologies to access a DWO in simulated harsh environments. Participants conducting a simple installation task responded positively to the use of a smart phone and AR glasses in accessing the DWO despite the clear distinction between devices. None of the participants had ever experienced AR glasses in practice as opposed to the phone with which most people were highly familiar. Performance outcomes were highly related to the design features of hardware, software, task, working environments and individual characteristics. These interactions illustrate the potential for technology to increase complexity in the socio-technical system. Optimal human performance is achieved through systematically evaluating technology considering its fit to the users' purpose, capacities, and limitations.

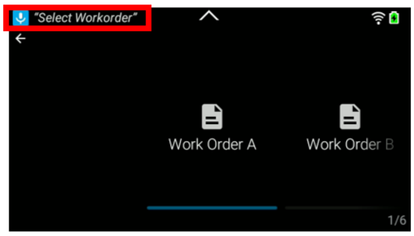
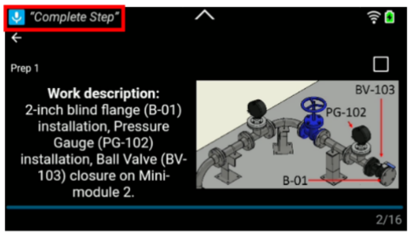
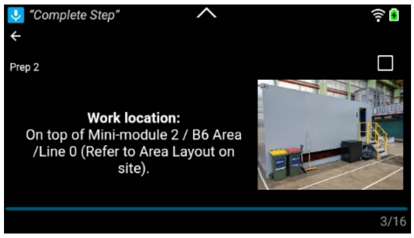
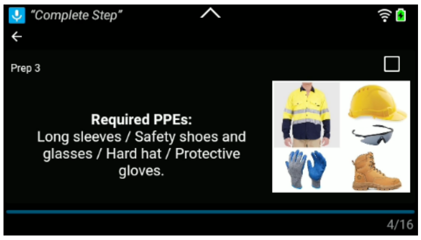
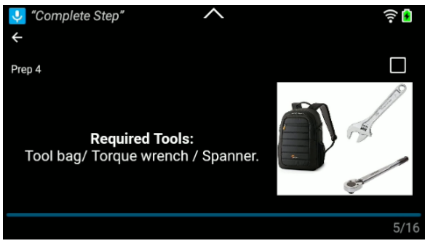
The claimed benefits and limitations of the two devices (smart phone and AR glasses) to effectively access a DWO were evaluated in this trial. No clear winner between the devices was established as both offer distinct advantages and limitations in different working conditions. It is evident that for successful implementation, HFE implications must be carefully considered, including task characteristics, working environments, software and user-interface design. Ease of use and achievement of task goals are key factors necessary to maximise business and individual benefits and minimise delays, errors, frustration and injuries.

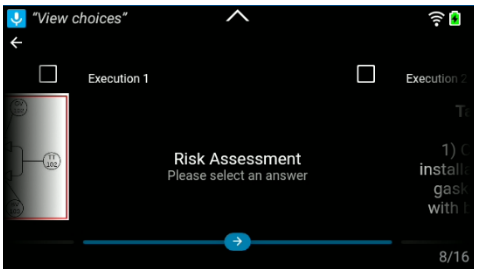
It is crucial for organisations to increase their understanding of how to identify and choose suitable tasks or processes that can be effectively supported by a DWO. Effort must be made to optimise processes since digitising a currently poor process will not promote successful technology adoption. This process should be in line with the analysis of hardware and software options available in the market to maximise benefits to the workforce and organisations. Given their inter-connectedness, end-users, industry leaders and associations, manufacturers, and researchers are important catalysts in accelerating the uptake and diffusion of DWO technologies in the Australian shipbuilding and manufacturing industries. There are opportunities to share experiences and lessons learned from both technical and human factors perspectives through a form of open-innovation such as industry-linked research and case studies.

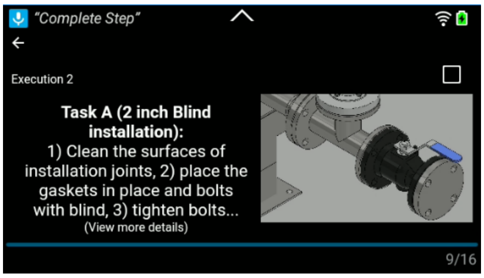
In preparing for the transformation that digital uptake will bring, businesses need to anticipate the nature of disruption and their desired future state by considering the new skills and workforce characteristics that will be required. Selection, recruitment, training and implications for job design will be critical and require change to current practices and philosophies. Ongoing, clear communication is the foundation on which to build these activities and draw on the knowledge and experience of the workforce. Including the workforce as the ultimate users of the technology will promote buy-in and enhance acceptance of technology during the adoption process.

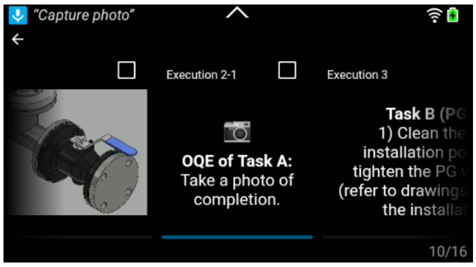
While this trial assessing the human factors of technology in harsh environments has provided practical results, the findings are only indicative due to the small sample size of 24 participants. To increase the reliability of the findings, future trials should increase the size and experience base of our sample (about half of the trial participants were from the shipbuilding industry but did not have specific practical experience of work in harsh environments; and only about one quarter were from the manufacturing supply chain). Greater breadth of participants would enable us to evaluate trial performance in a wider industry context to ensure relevance of the DWO and portable digital technologies in shipbuilding and along the supply chain.

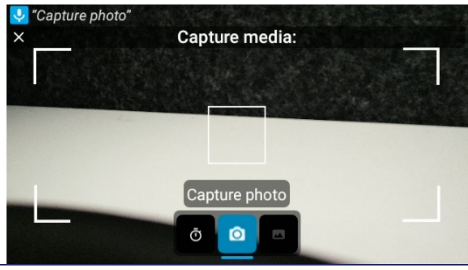
# Appendix A. Digital work order process

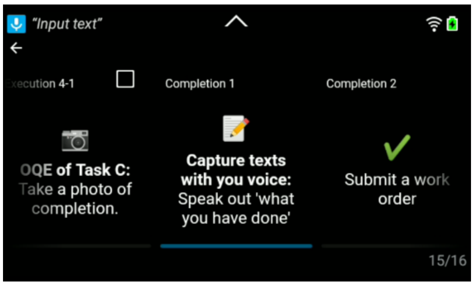
| Step | Process | User's View |
|---|---|---|
| Induction<br>(15min) | • Verbal presentation will be provided, including participant information sheet, consent form, technologies, safety aspects, opportunities for questions<br>• This will include introductory training session with different devices (Mobile & Google glass) for successful trial execution | |
| Start<br><br>(2 min) | Select '**Work Order Trial app'** -> '**Start a new work order**' -> '**Work Order A or B or C'**<br><br>Users can navigate or take action with **voice command**. Different voice commands will be seen as you go on the screen. |  |
| Preparation<br><br>(8 min) | Review the work order and tick all the boxes by tapping the step or saying "**Complete step**".<br><br>These include:<br><br>• **Prep 1) Work description**: 2-inch blind flange, Pressure gauge installation and Ball Valve closure on a module.<br>• **Prep 2) Required PPE**: Long sleeves/ safety shoes/ protective gloves (knee pads will be available).<br>• **Prep 3) Required Tools**: Tool bag/ spanner (12 inch or No. 27) x 2ea (Receive from Storage, B6 Area)<br>• **Prep 4) Required Parts**: 2 inch blind flange (B-01) * 1ea/ 2 inch gasket * 1ea/ bolts * 4ea/ Nuts * 8ea/ pressure gauge (PG-102) * 1ea (receive from storage, B6 Area)<br>• **Prep 5) Work location**: one of the locations will be given depending on the work order (C4 Area, refer to Area Layout on site) | <br><br><br> |

<table>
<tr><th>Step</th><th>Process</th><th>User's View</th></tr>
<tr>
<td>Execution<br><br>(12 min)</td>
<td>Perform the tasks with execution description AND capture OQE by taking a photo. Executions include:
<ul>
<li>Exec 1) Risk assessment: Q1) I am fit to perform the tasks, Q2) I don't have any hazards above, below, behind or inside, Q3) Hazards are effectively controlled, Q4) It is safe to proceed</li>
<li>Exec 2) Task A (2-inch Blind installation): 1) Check condition of installation surfaces, 2) Put the gasket in place and bolts with blind, 3) Tighten bolts and nuts, 4) Check installation condition</li>
<li>Exec 3) Task B (PG installation): 1) Clean condition of installation surfaces, 2) Install and tighten the PG, 3) Check the installation condition</li>
<li>Exec 4) Task C (Valve closure): 1) Find BV-103 (refer to drawings attached), 2) Check the direction of closure, 3) Unlock a handle collar, 4) Close the valve.</li>
</ul>
</td>
<td>








</td>
</tr>
<tr>
<td>Completion<br><br>(3 min)</td>
<td>Complete the work order by:
<ul>
<li>Comp 1) Capture texts with you voice: Speak out 'what you have done</li>
<li>Comp 2) Submit a work order</li>
</ul>
</td>
<td>


</td>
</tr>
</table>

# Appendix B. Statistical analysis

Parametric statistics assume that the measure being analysed has a normal distribution where most of the data points fall around the middle/mean value and less data points fall at more extreme values or further away from the mean[16]. A normal distribution is symmetrical and resembles a bell shape. The distrubition of data can be assessed through a test for normality; a significant Shapiro-Wilk test (more appropriate for sample sizes less than 50[17]) indicates that the data are not normally distributed and the assumption has been violated. Often in this instance, utilising non-parametric statistics is advisable.

The parametric statistic used to compare performance of the same task using two devices (i.e. the iPhone and the Google glasses) is a paired samples t-test. However, sample size influences the distribution of data with smaller sample sizes and is often likely to produce data with non-normal distributions, thus violating this assumption. When this occurs, as is the case for the current data, non-parametric statistics are employed.

Non-parametric alternatives to a paired samples t-test are the Paired Sample Wilcoxon test (Wilcoxon Signed-Rank Test) or the sign test. Each of these tests also has several assumptions about the charactertistics of the data, summarised in Table 6 below. Sign tests were conducted for the trial data due to better alignment with the assumptions.

**Table 6: Assumptions of non-parametric alternatives to the paired samples t-test**

| Wilcoxon Signed-Rank Test | Sign Test |
|---|---|
| The dependent variable (i.e. performance measure) should be measured at the ordinal (e.g. rating scale) or continuous level (linear scale like seconds, height | The dependent variable (i.e. performance measure) should be measured at the ordinal (e.g. rating scale) or continuous level (linear scale like seconds, height) |
| The independent variable (i.e. type of device) should have two categorical related groups or matched pairs (i.e. same person present in each condition) | The independent variable (i.e. device type) should have two categorical related groups or matched pairs (i.e. same person present in each condition) |
| The distribution of the difference between the performance scores of each device type needs to be symmetrical in shape | The paired observations for each case/participant need to be independent, i.e. one participant's data cannot influence another participant's data |
| | The difference scores are from a continuous distribution (i.e. data can take any value within a specified range, such as non-integers/decimal values) |

*Source: Adapted from Laerd Statistics (https://statistics.laerd.com/spss-tutorials/sign-test-using-spss-statistics.php)*

The sign test assesses whether the median of the difference between scores on a measure is zero. A significant result indicates the median difference is not equal to zero and there has been an increase or decrease in the median score.

---

[16] This Appendix is adapted from

Howard, S., Rajagopalan, A, Manning, K., O'Keeffe, V., Hordacre, A.L. & Spoehr, J (2021). *From ship to shore. Reducing the barriers to collaborative robot uptake in shipbuilding and manufacturing through human factors.* Adelaide: Australian Industrial Transformation Institute, Flinders University of South Australia.

[17] See https://statistics.laerd.com/spss-tutorials/testing-for-normality-using-spss-statistics.php

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