VIRTUAL REALITY AND AUGMENTED REALITY ON HUMAN PERFORMANCE

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Declaration

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

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Working on this thesis further enhances my knowledge on augmented reality be it on the advantages, disadvantages and also as a developer and what goes behind making augmented reality viable and enjoyable to the user. I hope augmented reality will be more acceptable with the masses and hardware advances occur in the near future.

Summary

Virtual Reality and Augmented Reality combine virtual and physical environments to create an enhanced and immersive experience to the user. This ability creates new mediums of providing information for task completion guidance. There are currently many different ideas and concepts on their implementation with the different types and modes of display. Major display devices include the spatial augmented reality display, head mounted display and handheld display. The modes of projection can be a video see-through display or an optical see-through display. Despite the interest and success in research on assessing their impact on human performance, there are only a few deployments in industries. This thesis looks upon the following: current state of the art of virtual reality and augmented reality, their potentials and usage in several industrial application and the operation of virtual reality and augmented reality from the technology's standpoint and the user's standpoint. A lab-based experiment was performed to study some of the hypotheses formulated from my research. Handheld devices of different forms: a head mounted device with a mobile device and a mounted tablet device projecting using video see-though display method were used in this experiment. These devices are chosen as it is the most feasible implementation on non-critical tasks. The results showed that an implementation of modified handheld devices for AR projection is feasible using commercially available devices. Depth perception still posed as an issue when using such video see-through devices, but the experiment showed insights of the nature of the task and the hand eye coordination of the user being able to offset this impact. The experiment also provided further understanding on the impact of this technology on human performance such as receptiveness to the device. More research is to be performed to find a quantifiable experimental framework for implementing virtual reality and augmented reality.

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List of Abbreviations

VR	Virtual Reality
AR	Augmented Reality
MR	Mixed Reality
AV	Augmented Virtuality
HCI	Human Computer Interaction
SAR	Spatial Augmented Reality
HMD	Head Mounted Display
AI	Artificial Intelligence
3D	Three-Dimensional
2D	Two-Dimensional
PET	Positron Emission Tomography
fMRI	Functional Magnetic Resonance Imaging
EEG	Electroencephalography
CAS	Computer Aided Surgery
MIS	Minimally Invasive Surgery
CAD	Computer Aided Design
GUI	Graphical User Interface
ACT-R	Adaptive Control of Thought-Rational

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Chapter 1: Introduction

1.1 Background

In Milgram et al’s proposed “Reality-Virtuality Continuum” [1], lies definitions of virtual environments based on the percentage of the real and virtual world. A fully virtual environment would be termed “Virtual Reality” (VR) and at the other end of the spectrum would be the “Real World”, the environment we are currently experiencing. Augmented Reality (AR) refers to an enhanced version of the real environment by overlaying virtual information to enhance the real environment; Mixed reality (MR) refers to virtual products interacting with users in the real world; and Augmented virtuality (AV) is a subcategory of MR which refers to the merging of real-world objects into the virtual world. The entire spectrum is represented with Figure 1 below. Nowadays, anything less than VR is relatively interchangeable as all forms of virtual objects serve a multitude of purposes and utility [2]. For ease of referencing, AR will be used to coin anything in between. Nonetheless, a useful virtual environment and virtual objects should be able to seamlessly interact with the user and the interactions are immersive to the user.

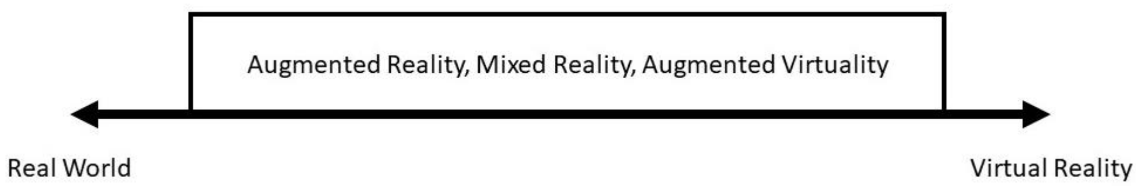

Figure 1. Modern Reality-Virtuality Continuum Spectrum

VR and AR allow people to connect the virtual environment with the physical world. This technology is becoming increasingly popular in the current generation where it is used in various avenues such as entertainment, education and in the workplace. Gamers are able to bring out the gaming world out of their computer screens and into the physical environment, artists can integrate digital work with the physical space, 3D objects can be easily projected to allow students to visualize effectively, and additional information can be provided to aid workers easily. Ultimately, the aim of VR and AR is to provide a more interactive, efficient, and safe environment to the user.

VR and AR does not consist solely of superimposing or display visuals. VR and AR apply to all senses which include smell, touch and hearing as well [3]. A good VR or AR device should be able to make the virtual objects appear to coexist with the real environment, making the users feel immersed in the new combined environment. This immersion is the measure of the level of “real-ness”. Users should also be able to interact with the virtual information with calibrated and programmed instruments which fall under the category of human-computer interaction (HCI), consisting of different means humans can manipulate the virtual information. Examples of HCI devices include a modern keyboard with manual buttons to hand motion and speech recognition.

1.2 Types of VR and AR Displays

The three main types of VR and AR display currently available are: Spatial augmented reality (SAR) displays, head mounted displays (HMD) and handheld displays. Some types of display only allow for AR display and some for both VR and AR display.

1.2.1 SAR Displays

SAR generally consist of a tracking device such as a camera or a sensor and a visual projection device such as a projector, video, or hologram. SAR brings the virtual environment to the user and the user do not need to hold onto any projection devices too. The user will be able to interact with the virtual objects through sensors situated around the environment or an HMI device such as a calibrated controller. Since the virtual objects will be projected into the environment, it allows other users to view the same virtual projection at the same time [4].

1.2.2 HMD Displays

As the name suggests, HMD is worn on the head of the user as part of a headgear which places both images of the real and virtual world over the user's direct field of view. AR HMD is particular in this case, it can either be video see-through or optical see-through which will be explained in later chapters. Both of these display types have their own advantages and disadvantages from either a user's point of view or the developer's point of view. Virtual objects displayed will be solely for the wearer and multiple people are not able to view it at the same time. However, the overlaying of information directly into the user's direct field of view results in a more immersive experience and in turn, allows the user to stay focused for a longer period of time [5] [6].

1.2.3 Handheld Displays

Handheld displays are mobile devices, including the cellular devices that everyone is currently using on a day-to-day basis. Handheld display only consists of video see-through capabilities to overlay a processed real environment by the camera with the virtual objects. The processing power of a mobile device cannot be compared to a computer due to nature and the capabilities of handheld devices. Fortunately, recent technological advancements allow large and popular technology companies such as Apple and Samsung to create commercial handheld devices capable to handle such processes.

1.2.4 Comparison of Display Devices

The three main display systems have their own unique advantages and disadvantages. The qualities can be grouped and gauged using various qualitative and quantitative analysis. Ergonomics is one of the key factors determining the user experience and the performance while using the device. The most common issue especially in the modern technological era is the conflict between prescription spectacles and HMD [7]. Prolonged usage of the HMD may result in discomfort of the user due to the weight and the processing of virtual objects by the device [8]. As the name suggest, handheld devices limit the user's dexterity due to the need of holding on to the device while using it [9]. SAR though feels the most natural to the user and does not limit any of the user's limbs, the angle of projection and direct line of projection must be carefully calibrated in order to display the most natural and unobstructed virtual objects [8].

Pre-notion and bias will also affect the quality of the experience when using the different devices. As almost everyone is familiar with a smartphone due to constant usage in their daily lives, smartphone VR and AR applications are generally well received [10]. Gamers are also more receptive and perceive the virtual information better than non-gamers. The ease of deploying the display device is also a factor on when implementing VR or AR. Handheld devices are easier to calibrate and deploy due to the simplicity and everyone will own a handheld device like a smartphone [11]. SAR devices, however, tends to require careful calibration of the position and angle of the projection. HMD can be relatively expensive and not very versatile in some situations [12]. Table 1 compares the advantages and disadvantages of various devices.

Table 1. Comparison of Display Devices

Display system	Advantages	Disadvantages
SAR Device	Natural & fixed overlay	Not portable
	Allow group collaboration	Shadow casting
	Comfortable to use	Difficult system calibration
HMD Device	Hands free	Ergonomic problems
	Consistent viewing focus	Only allow single observation
	Allow see through of the real and virtual world	Depth Perception
Handheld Device	Easily deployable	Limited field of view
	Mobile	Indirect perception of the real world
	Easily acceptable	Not hands free

1.3 Motivation

The Fourth Industrial Revolution, otherwise commonly known as Industry 4.0 was introduced to the mass public by Klaus Schwab [13]. It refers to a new phase in the industry revolution that focuses on modern smart technology such as automation, artificial intelligence (AI) and advanced HCI in the manufacturing industry. Besides the manufacturing industry, this digitisation can be applied across the board of industries such as medical, healthcare etc.

In the current engineering workplace, additional information in needed to aid in task completion as the industry becomes information heavy. Such tasks include assembly processes in the engineering line where operators refer to the next step to be performed or additional information due to an information lapse while performing on the task. Virtual information in the most common form of tablets and phones are used to display additional information due to its ability to display only one information at a time and able to store much more information within a small device as compared to bring around books and papers. This means that the world is shifting towards the use of virtual information display regardless of the type of device. VR and AR has become a popular form of display of virtual information due to its novel concept but is currently not the most acceptable form of display due to its limitations, lack of purpose, and resistance to change which will be explained further in later chapters.

Extensive research has been performed on the latest VR and AR technology and its capabilities in increasing human performance. However, there are many more factors to be included when industrialising VR and AR into the workplace. Factors such as cost, scalability and deployability which are often not discussed when assessing technological devices determine the final outcome of implementing the technology into the workplace. In the current engineering workplace in Singapore especially, the demographic of operators and technicians are those who are not technological savvy. This will bring about resistance to change and biasness towards new technology. The closest VR and AR display device that could be feasible in implementing into the workplace in the near future would be the handheld display device. The handheld display device is the most cost effective and easy to develop and deploy into the industries. In addition, the receptiveness of handheld devices would be higher than the other two main devices.

1.4 Objectives and Scope

The objective of this thesis is to evaluate human performance using VR and AR devices in order to evaluate and improve the framework of the effectiveness in implementing these technologies into the workplace. Particularly focusing on the AR technology as its ability to be used in an operational setting. The definition of human performance and the different modes of display will be discussed. The effectiveness of VR and AR currently being researched will be reviewed. In addition, the physicality and psychology of the user will be studied in order to fully understand the operations of using VR and AR. Particularly, how the human eyes which are the main senses reacting to the virtual environment/objects and the cognitive architecture for understanding human cognition will be discussed. Lastly, an experiment on using everyday electronic devices will be carried out to find out and understand the complexity of implementing video see-through AR into completing a non-critical tabletop task. A mounted tablet device and a mobile device with a head mounted mount will be used to compare with a traditional tablet device on completing encoding and decoding tasks.

1.5 Thesis Organisation

The thesis is organised as follows. Chapter 2 explains the theory of the human performance and AR projection methods. Chapter 3 showcases the current research performed on the effectiveness of implementing VR and AR into the industry. Chapter 4 studies the physicality and psychology of the users. Chapter 5 will discuss an experiment conducted to evaluate the effectiveness of modified handheld AR devices. Chapter 6 will conclude and discuss some of the possible future work of the research of VR and AR.

Chapter 2: Human Performance and AR Projection Modes

AR is different from VR as it has different modes of projections. This chapter further understands the two different modes namely, Optical See-Through AR and Video See-Through AR. Both modes of display present different possibility and limitations to both a developer and the user. In addition, the human performance parameters will be discussed and the methods to assess these parameters will be explained in this chapter too.

2.1 Video See-Through AR and Optical See-Through AR

2.1.1 Video See-Through AR

Video See-Through AR devices present video feeds from the camera of the device. This is most commonly attainable through the use of a handheld device which could be accompanied with a headset or mount. As the virtual images and real world are presented simultaneously through the device's camera, image enhancement can be performed. The brightness of the real environment and the AR objects can be adjusted accordingly and mapped accurately as the processing happens on the same pipeline. This allows a more immersive experience to the user and easier development of applications.

However, the real world is translated through the device's camera feed and displayed on a flat screen. This results in the real-world environment to be transformed from a three-dimensional (3D) environment to a two-dimensional (2D) environment. A reduction of depth perception occurs which might hinder the user from navigating through the real-world environment. The reduced depth perception results in slow visualisation of the environment and in turn, slower and less accurate performance [14]. In addition, if the processing power of the device does not have the capability to handle the application, latency issues and lag will occur which negatively affects the user's performance such as speed, accuracy, and hand eye coordination [15] [16]. Thus, video see-through AR devices are usually not used in situations where the environment is more critical than the information displayed such as a military operation.

2.1.2 Optical See-Through AR

Optical See-Through AR combines virtual images with the real environment. This is performed usually through the use of slanted semi-transparent lenses. With the user being able to see the real environment, it allows the user to navigate around at ease. Allowing the viewers to be able to view the real world when augmenting the virtual information might lead to better perception of the virtual information too [17].

Optical See-Through AR caused users to have an X-ray vision effect which is the intention of some application. Such as viewing piping in walls or the organs of a patient. However, x-ray vision effect is an unnatural view to some users, and it requires great difficulty in presenting the virtual information accurately in order to have a positive effect due to the virtual overlay [18]. Occlusion is also an issue which is making the virtual object partially transparent and overlay it behind real objects in order to correctly represent the depth of the virtual objects [19]. Some optical see-through AR devices are partially capable of occlusion, but they are currently too bulky and only capable of displaying a limited field of view.

Light intensity will affect the optics of the virtual display. A brighter light source from the surroundings will dim the virtual image displayed by the device. A manual translation and colour correction of the real-world [20] is required to ensure that the virtual objects are accurately overlayed onto the real environment. This is usually accompanied with additional coding, calibration and hardware sensors while wearing an optical see-through AR device. This results in a higher cost to develop and deploy an optical see-through AR device. Though optical see-through AR displays allows the user to still operate in a mission critical task without sacrificing dexterity and awareness with the surroundings, it loses the fully immersive experience if the virtual objects are displayed inadequately or requires extensive hardware to complement the experience.

Optical See-Through AR devices also suffer from latency problems which affects the performance of the user. Though recent work has succeeded in reducing latency of optical see-through AR devices to 1ms [21], off the shelve devices are incapable to match these standards which makes industrial implementation not feasible. Research showed that although high latency results in negative performance, the latency difference between the real-world and virtual objects affects the performance of the user too [22]. The larger the difference, the larger the detrimental effects on the performance and this magnitude will be larger than if the latency of the real world and the virtual object is high but similar. This makes video see-through devices superior as both the real world and the virtual objects have the same latency and strengthens the concept that an accurate overlaying of information is more important than latency.

Nonetheless, latency is subjective to the scenario being implemented on. Some scenarios require all latency to be of minimal levels and some require matching of the virtual and real-world latency. Some examples include military training and missions where the real-world is of outmost importance or during simulation training where the virtual objects need to match the activity of the real world.

Table 2 states some off the shelf AR display products currently available in the market.

Table 2. Commercial Display Devices

Video See-Through Devices	Optical See-Through Devices
Samsung Galaxy S20 with Samsung Gear VR, SG$1,400 [23]	Microsoft HoloLens 2, SG$5,388 [26]
HTC VIVE COSMOS, SG$1,229 [24]	Magic Leap 1, SG$3,080 [27]
iPad 2021, SG$1,199 [25]	Vuzix Blade Smart Glass ,SG$799 [28]

As shown, the prices of the different off the shelf AR devices can be quite costly and they range in capabilities according to the price. In general, video see-through devices are cheaper than optical see-through devices due to the hardware needed to calibrate the virtual objects onto the real world. In addition, video see-through devices are mostly daily consumer products which possess other functions too.

2.2 Human Performance Parameters

The standard parameters of measuring task completion qualities are time, accuracy, and mental workload [28]. A positive increase in human performance would indicate an increase in task completion rate, reduction of errors and a reduction in cognitive demand. In real-world practice however, not all three measures will be improved at the same time and in certain occasions, these measures may trade off in respect to each other.

Furthermore, there are more measures that could be considered which do not necessarily directly related to human performance. Examples such as the degree of learning, memorising information, quality of mental models when visualising an object, situation awareness while concentrating on the current task, emotion, confidence, critical thinking to execute the best decision and hand eye coordination. All these cognitive measures though could not be measured qualitatively when accessing the performance while executing a task, they still can be expressed indirectly and should be considered when considering improving human performance with a new implementation.

2.2.1 Time

Time is the most fundamental measurement of accessing any form of performance. It is a strict quantitative measurement and hence easily the most non-arguable measurement whereby the one with the least amount of time used to complete the given task will be deemed more superior than the other.

2.2.2 Accuracy

Similar to time, accuracy is easily quantified and a measure that firmly determines the performance of a task. The degree of impact due to accuracy varies from task to task such as a spelling mistake which could be rectified easily to a misjudgement when performing a critical surgery that affect the lives of the patients. Accuracy easily measures the performance of completing a task.

2.2.3 Cognitive Workload

There are different qualitative and quantitative methods to measure cognitive workload. They are split up into three different categories, task measurement, subjective rating measurement and physiological measurement. Task measurement refers to the measurement of performance of a given task and the performance is graded in terms of other measurements such as speed and accuracy after the participant is subjected to different forms of induced cognitive fatigue such as lack of sleep or distractions [30]. Task measurement can also be measured by giving a secondary task which emulates closely to the primary task and similarly, the participants are induced with cognitive fatigue and graded when the secondary task is completed [31]. However, such methods are not fully reliable as they only find a correlation of either task to the induced cognitive fatigue and it is not easy to control the induced cognitive fatigue. The measurements collected are not a definitive measurement to cognitive load too.

Subjective rating measurement is another form of cognitive measurement and it consists of having the participant grade the level of perceived cognitive workload relative to the participant. One of the most popular methods are that of using questionnaires such as the NASA-TLX [32]. It rates perceived workload in order to assess a given task which can be used to evaluate the performance of execution of task. The total workload is divided into six other subcategories namely:

1. Mental Demand
2. Physical Demand
3. Temporal Demand
4. Performance
5. Effort
6. Frustration

The subcategories are rated within a 100-points range with 5-point steps. These ratings are then combined to a task load index. The second part of the NASA-TLX requires the participants to weigh the individual subscales by comparing them pairwise based their perceived importance.

This means that the individual subscales are gauged on how much relevance is it to workload. The number of times chosen is the weighted score [33]. This is multiplied by the scale score and then divided by 15 to get the finalised workload scale from 0 to 100, otherwise known as the overall task load index. However, many researchers ignore this pairwise comparison which is acceptable and refer the test as “Raw TLX” [34]. There has been evidence supporting this form of evaluation and increase the experiment validity using the “Raw TLX” [35]. In addition, the individual subscales can be dropped if it is irrelevant to the task.

With the rise in technology available, physiological measurements can be measured and give a quantifiable measurement. Individuals who are subjected to some degree of cognitive workload usually exhibit changes in various physiological forms. However, not all physiological change in humans determine a strong link to cognitive load for example, blink rate [36], hormone levels [37] or blink duration [38]. Nonetheless, there are effective measurements that have a strong connection to cognitive load. These measurements are currently widely used in neuroscience such as positron emission tomography (PET) [39], functional magnetic resonance imaging (fMRI) [40] and electroencephalography (EEG) [41]. These measures though are sensitive and have the ability to consistently reflect the minute changes to cognitive load, can be quite intrusive and cumbersome to deploy. PET scans register changes in blood flow related to neural activity and requires the participant to ingest hazardous materials. fMRI requires the participants to lie in restricted positions. EEG on the other hand, is a non-invasive measure that measures electrical activity produced by the brain collected by the electrodes placed on the person’s scalp. These measurements are historically able to predict in response to cognitive stimulation [42] [43]. EEG also come in wireless forms [44] which makes it easy to deploy and study the participants when executing a given task is being assessed. However, due to its non-invasive nature, EEG has low spatial resolution and is easily subjected to interference and noise through natural body movements such as blinking and breathing. Various solutions are currently researched and implemented to remove such noise from the collected EEG data [45] [46], making EEG one of the more reliable methods of collecting cognitive workload [47].

2.2.4 Hand Eye Coordination

Hand eye coordination is the simultaneous processing of the visual input to the eyes and the corresponding control of the hands. It is a fine motor skill, and the level varies from each individual due experience, natural talent, or disorders [48] [49]. Hand eye coordination is an important skill in order to perform daily activities. Athletes and other professionals rely on hand eye coordination skills to succeed in their area of expertise. With hand eye coordination being an important skill for survival, numerous methods to access and train hand eye coordination are formulated [50] [51] [52]. The traditional method of accessing hand eye coordination is through visual supervision or through the performance of secondary task [53]. However, this proves to be unreliable and not could not be quantified or compared easily. Similar to assessing cognitive load, EEG can be used to assess hand eye coordination quantitatively.

Using EEG to assess fine motor skills have proven success in cross-sectional studies between different skill levels. A difference in the EEG bands were found for different tasks of varying skill levels. For example, alpha power in the left temporal region is associated with the level of marksmanship shooter, a better shooter possessed higher alpha power and vice versa [54]. A difference in theta band at the frontal region separates the skill level of golfers [55] and an attenuation of alpha band at the frontal channels with a higher hand eye coordination mastery [56]. There are different methods employed to further interpret EEG data accurately and study the relationship of the EEG data collected with hand eye coordination. Lempel-Ziv Complexity [57] is one of the popular methods of categorizing the EEG signals and sequences. Classifying mental fatigue [58], identifying Alzheimer's disease [59] and classifying genomic sequences [60] are successful implementation of the use of Lempel-Ziv Complexity.

Similar to assessing cognitive load with EEG, the result from the spectral analysis is often highly variable among different people and is prone to external noise and factors. The difficulty and the length of task also affects the classifying results [56]. Thus, studies need to be cautious in the way it is conducted, and the interpreting and cleaning of data needs to be performed optimally in order have an accurate understanding of the EEG data. Nonetheless, EEG results in a quantifiable alternative to understand and assess hand eye coordination skill.

Chapter 3: Using VR and AR for Human Performance

The integration of virtual objects and virtual environment with the real world can open up different opportunities to improve the quality of task performing. From learning to execution, different industries benefitted greatly from this technology. Industries such as military and healthcare are able to simulate scenarios that are not easy or ethical to replicate in order to train the users. Design and manufacturing gain from the increase in avenues to allow visualization of the design and ideas to allow an improved expression of what is needed to be expressed. This section will discuss on the current research on the effects of VR and AR in some of the common usage.

3.1 Augmented Reality in the Surgical Room

Computer assisted surgery (CAS) is the integration of the computer technology for surgical planning, guiding, and performing of surgical interventions. This is due to the increasing technology of obtaining accurate medical images and scans before the actual surgical procedure which allows the surgeon to plan and an increased guidance during the surgical procedure. There are many advantages to computer assisted surgery which brings success in the completion of the surgical process [61] [62]. However, the traditional method of CAS consists of a "heads up" posture where the surgeon faces the screen which is located facing him instead of the position of the patient [63]. This posed a challenge to individuals who do not have excellent spatial awareness or hand eye coordination in order to complete the surgical procedure effectively. This led to the introduction of AR into the surgical room to improve the overall experience within the surgical room [64]. As AR overlays the information onto the real environment, the information obtained can be overlaid onto the patient, resulting in a "See-Through" display to make the movements more natural to the surgeon [63]. The virtual information can be overlaid with the main AR display devices i.e., SAR device [65], HMD [66], or handheld/tablet devices [67]. With increased network technology, live images can be sent over with the camera probe and immediately overlaid onto the patient without the need of obtaining pre-surgical medical images [68]. This creates the “x-ray’ vision during a CAS.

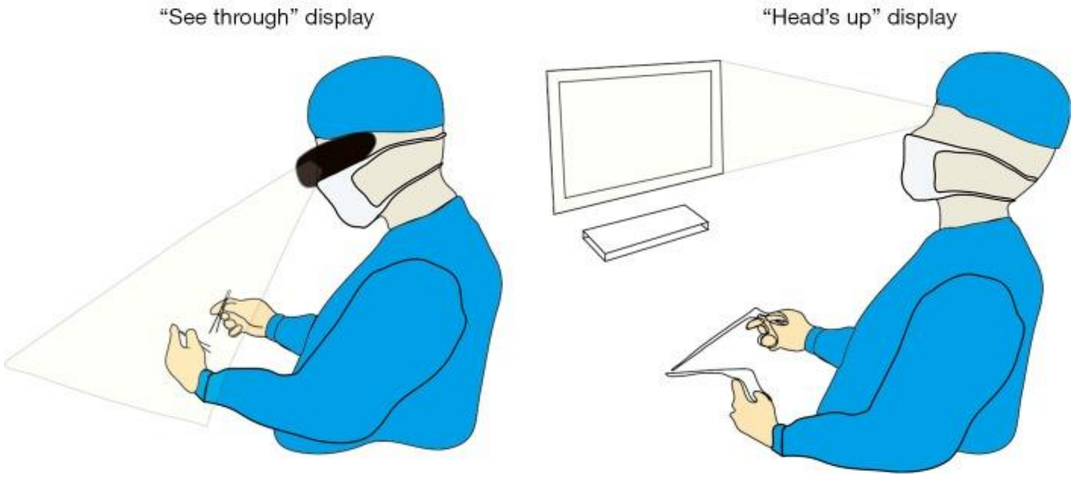

Figure 2. Surgeon Posture with AR vs CAS [63]

Surgical procedures which require a high level of precision such as radiofrequency (RF) ablation (RFA) of tumours benefit from the AR projections to help guide surgeons during the procedure [65]. RFA is a medical procedure which uses medium frequency alternating current to ablate tumour or dysfunctional tissues in the human body. A RF needle is inserted into the human body to reach the problematic tissues and the current from the needles will remove these tissues. The role of AR during this surgical procedure is to overlay the medical images obtained before the surgical procedure onto the patient. This improves the accuracy of the positioning of the needles which will greatly reduce accidents and improves the overall success of the surgery [69]. The RF needles can also come in a surgical robot form which holds on to the RF needles and improves stability of insertion. As the surgeons’ hand might move due to natural movement of the body [70]. The tracking capabilities of AR allows the introduction of hand gestures to control the position of the RF needles to allow the control to be more natural and an alternative method in the event that the surgeon is unable to touch the equipment [70].

Oral and maxillofacial surgery is a surgical procedure involving rectification of injuries and defects regarding the head, face, neck, and jaws. Surgical procedures of oral and maxillofacial surgery involve the use of fiducial markers and trackers. The main drawback of consists of unintentional line of sight blocking and errors caused by a shift in the markers while during the surgery [71] [72]. Especially when the area around the head is small, introducing additional physical guidance in the surgery will tend to cause a nuisance instead of additional benefits while performing the surgery. Thus, the introduction of AR into oral and maxillofacial surgery will tackle these problems. The virtually planned maxilla and the actual position can be superimposed thus improving the accuracy and improves the 3D perception of the surgeon [73]. One unique finding for introducing AR for oral and maxillofacial surgery is the lack of impact of depth perception while using video-see through AR. As discussed in Chapter 2, Video-see through AR will cause a problem in regard to depth perception which results in a reduction of accuracy and hand eye coordination. However, as the distance between each object and marker is in a small and reasonable range, the uncertainty while navigating in a 3D environment using a 2D display is manageable [74].

Overall, introducing AR into the surgical room will increase the overall experience of CAS. The posture of the surgeon, hand eye coordination, 3D visualization and accuracy of the surgical procedure are improved. This will increase the success of the surgical procedure and making it safer for the patient. However, clinical standards have not been updated and hospitals are not receptive to AR due to the possible risk and effects during slips while using the technology. The increase in visual cues to guide surgeons might distract the surgeons by taking away their attention from the patient to the visual overlays instead [75]. The surgeons might over rely on the visual cues instead of the situation currently happening, thus resulting in a false judgement. Despite the growth of network capabilities, lags will still occur and especially when the human eyes are especially sensitive to changes in visual cues, when the AR is not superimposed correctly at the right time or position, it will affect the surgeon negatively while performing the surgical procedure [76]. Nonetheless, the possibilities of AR in the surgical room extends further than these 2 types of surgical process such as minimally invasive surgery [77] and remote robotic surgery [78]. Both the technology and protocols need to further improve in order to integrate AR seamlessly into the surgical room.

3.2 Virtual Reality in Medical Training

Junior healthcare professionals and medical trainees do not have the luxury to practice medical procedures at their convenience due to safety of the patients. Almost all medical procedures are critical tasks that may involve lives and the health of patients. In addition, some medical procedures such as the minimally invasive surgery (MIS) requires a high level of hand eye coordination. MIS has risen in popularity over the years due to benefits such as a reduction of blood loss, a reduction in tissue impact the reduction of possibility of endangering the lives of the patient. Besides having good hand eye coordination, critical thinking and reacting to minute changes are also important skills to have while performing this medical procedure. Thus, there is a need provide effective and safe avenues to educate junior healthcare professionals and medical trainees.

MIS is an image-reliant procedure that requires surgeon to navigate the intended areas in the human body with surgical tools. The image is relayed by a camera probe which transmit to a monitor screen above the patient. Coupled with the lack of visual information due to the camera's capture view, MIS requires surgeons to have an excellent spatial awareness of the tools and the patient's body and good hand eye coordination is needed in order to control the equipment and not hurt the patient unnecessary. Training for MIS traditionally involves a computer with a keyboard and a mouse. There is a lack in the transfer of skills to the trainee surgeons [79] due to lack of performing the actual motion or having an immersive experience to be engaged in the procedure. VR is a good platform to provide a safe, immersive experience, and an effective transfer of skill to the surgeon trainees [80]. Different surgical procedures that are considered a MIS surgery benefitted from utilising VR such as laparoscopy, percutaneous coronary interventions [81] [82] to polymethylmethacrylate (PMMA) injections [83]. Since VR is a virtually simulated environment, different scenarios can be artificially created to the trainees to prepare them for different situations. HMI controllers are also used during the VR simulation to control the virtual surgical tools in order to let the surgeon trainees practice holding and the actual motion during the MIS. Developed systems will also have an upgraded HMI controller to provide haptic feedback in order to make the training more realistic and immersive while using the VR application [84] [85]. Especially when the human body is delicate, having tactile feedback during the training process greatly improves the overall success and transfer of skills as compared to one that is completely visual [86].

VR can be used to train other aspects needed in medical procedures such as providing different scenarios where the user has to make critical decisions in a stressful environment [87] [88]. As VR can provide an immersive environment to the trainees, the process of learning and utilising critical thinking will be more embedded and efficient. The immersive experience of VR can also be used in non-critical medical procedures such as memorizing objects and procedures in the surgical or medical room [89].

Utilising VR for medical training will bring about a more efficient transfer of knowledge and it is not expensive to deploy the most basic set of equipment [90]. Especially with the Covid-19 pandemic, many students will not be able to freely participate or view a live medical procedure. Students are also positive towards adopting this new technology [91] due to VR being a novel idea and this will improve their learning experience overall. Compared to relying on literature as their only avenue. With the increase of AI technology, peripherals can be added to the application to further improve the learning experience [92]. The increase in network capabilities can also provide collaborative training [93] to allow medical trainees to practice together as some surgical procedures require a few surgeons working on it simultaneously. Despite many research successes in providing excellent results towards utilising VR to train the junior medical professionals and surgical trainees, it does not extend to those who are more equipped with the skill. This is due to the difficulty of modelling the virtual models and calculating and simulating the interactions between the virtual objects accurately. Nonetheless, there are efforts currently explored to improve the modelling process of the simulated virtual objects in the VR environment. As the human body is complex, different modelling tools are needed in order to predict and simulate the interactions of the virtual objects. Ranging from organs [94] [95] to blood flow [96]. A more realistic interaction of the virtual objects improves the immersive experience during the medical training which will result in a positive transfer of knowledge to the medical trainees [97].

In addition, AR can be used for medical training. Some of the upgraded traditional training consist of using virtual models and manikins to navigate tools in the manikins. AR is used to overlay additional virtual information onto the manikin to improve the overall immersion of the execution [98] [99]. Junior medical professionals and surgeon trainees will be able to experience using the tools and handle the actual tools in real life. As some of the manikins have a designed path for the tools to navigate around, it will solve the force feedback and navigating simulation problems VR is facing.

In the classroom which extends past medical education, AR can be used as an improved avenue to display information to make learning more interactive and interesting asides from using books. 3D information can be displayed to allow an increase in 3D visualisation for learning [100]. This allows a better transfer of knowledge and allows a more efficient learning process for students.

However, AR devices have their own device limitation which affects the overall learning process of medical procedures. Similar to VR, overlaying the virtual objects though improves the immersion experience, they limit at the visual level [99]. Modelling the interaction of the tools regardless of a virtual tool or physical tool still needs work to make the interactions realistic. In addition, as the environment is not virtual, there is a need for tracking of the real environment and not all display devices have the capability to provide pristine overlays [101]. Cost will be involved to mitigate and improve the tracking and overlaying capabilities and not everyone has the luxury afford it. Regardless of VR and AR medical training, utilising VR and AR is still in the early stages currently. Despite the numerous benefits or success research has presented on using this technology, most of the studies usually used a prototype which might not be robust to be evaluated. Most of the research used a secondary task to evaluate the success of the primary task i.e., using a similar task to gauge the effectiveness while performing the actual task. This method of evaluation might not be accurate when using it to evaluate the effectiveness of the learning process. A lack of a learning model is also presented in order to effectively deploy this method [102] [103]. Overall, utilising VR and AR as a means for medical training will be useful for junior medical professionals and surgeon trainees. More work in regard to the capability of the display devices and modelling the interactions of the virtual objects needs to be improved in order to make this implementation convincing and effective.

3.3 VR and AR in the Engineering Workplace

With industries becoming competitive, workers must constantly keep up to the standards to remain competitive in their workplace. Especially in the engineering workplace where it is information heavy. In addition, mundane skills are shifting towards automation leaving the workforce to execute cognitive heavy task. Not every worker is able to keep up with the constant advancement and retain the knowledge learnt [104]. Thus, VR and AR can be introduced to aid workers in completing their task efficiently within the engineering workplace.

Computer aided design (CAD) is key in the engineering industry. Parts and structures are designed virtually on the computer before being sent out to be built or manufactured. 3D geometrical visualisation is a key skill to be able to execute CAD projects efficiently. CAD is performed on a computer with a flat screen and thus, in some situations, it is hard to visualise a 3D design with a 2D screen. AR can be introduced to project the CAD components from the 2D screen into a 3D virtual projection [105]. The components can be projected onto the real environment with any display devices and designers can view the objects. Scaling of the components can be performed to gauge and visualise the object virtually before turning it to real life. With the integration of object tracking for VR/AR, the virtual CAD components can be manipulated with gestures [106] to allow a more natural HMI control. The ability of object tracking also allows the virtual objects to interact with real objects. Virtual CAD components can be overlaid onto the intended space to allow designers to better visualize the end product of the CAD component [107]. Overall, introducing VR and AR to CAD designers boost the 3D visualisation, thus reducing the cognitive load needed when designing over the 2D computer screen and indirectly making the design process more efficient.

An upgraded control of the workspace and operating of tools and machines can be realised with the use of VR and AR. At the most basic usage, additional information of the running machines and tools can be displayed using the AR technology. The workers can view and operate the machines and tools with a graphical user interface (GUI) [108]. This makes the information and operation more interactive to the workers which increases their efficiency in the workplace. Teleoperation of machines are also possible for example, attaching a camera onto the head of the robot and having the worker operate the robot with an HMD from another location. This allows the workers to operate robots and machines from a remote location in the event of the actual working environment being unsafe and not suitable for a physical presence [109]. Similar to the inclusion of peripherals, AI assistance can be introduced to aid workers for completion of task [110]. Coupled with the natural interactions with bare hands, workers are able to complete the given task in a quicker time and a reduction of physical demand as compared to traditional aids.

There are many different applications of VR and AR to aid workers in the engineering workplace. Each of them has their advantages and disadvantages. As all workers are of different age and background, not everyone will be fluent and receptive with the new technology. Some of the workers who were trained differently might not express an improved outcome when using VR and AR [111]. In addition of the difficulty of the task, assimilating VR and AR might not reduce the cognitive load for the task. The task might be too simple to need such a technology and the impact of the reduction of cognitive load will be not significant [112]. Or the controls and the overlaying of information might be overwhelming to the workers which increases their cognitive load to operate the technology [110]. Current VR and AR technology also heavily emphasize on visual display which neglects the haptic aspects which is essential in the engineering workplace too [113]. The lack of haptics during execution in the engineering workplace reduces the transfer of knowledge to the workers which will efficiently allow them complete or learn the given task [114]. Similarly, VR and AR can be used in engineering education to further help students during 3D visualisation or help understanding some of the interaction between the learnt parts. Overall, there is still a lack in the framework for implementing VR or AR onto the engineering workplace or education. Future trends of research should include other senses such as haptics and even augmentation of sound when assessing the capability of VR and AR in the engineering workplace. As the technology thrives in the workplace, research on the negative aspects due to dependency of the technology can be considered [114].

Overall, introducing VR and AR into the engineering workplace will bring about a positive impact to the efficiency and performance to the workers. However, there are still limitations of the technology that needs to be worked on before research can progress.

In summary, VR and AR can bring about a positive impact on human performance when utilising them on an industrial setting. Overarching results on the effects of VR and AR shows an overall reduced task completion time, increase in accuracy, and improvement in hand eye coordination regardless of primary or secondary task. However, findings on cognitive load are divided which stems from various reasons. Reasons such as the nature of the task and the background of the user affects the cognitive load while using the technology. As all humans are innately different and they receive different formal education, they have different experience and opinions on VR and AR. This may result in differing outcome when deploying the technology into the workspace. It is difficult to find a general framework for the transfer of knowledge using VR or AR nor an optimum method to implement the technology when executing a task. This is no surprise as every task has their own niche set of needs and fine tuning is needed to be done in order to assimilate the technology smoothly to make the given task more efficient.

Chapter 4: Human Physicality and Psychology

Besides researching on the capabilities and usage of a technology, a two pronged approach can be used whereby the research of users can be performed in order to fully understand the integration process of the technology. As shown in previous chapters, the success of the implementation of VR and AR for a given task is partially dependent on the user. In this chapter, we will understand the human physicality and psychology that contributes to the usage of VR and AR.

4.1 The Human Eye

VR and AR are still vision heavy display and thus, the human eye is the first thing that interacts with the virtual object and virtual environment first. The eye is part of the sensory nervous system of approximately 24mm [115] that reacts to light, allowing vision to be processed in the human brain. A person with normal vision can see from 25cm to a relatively large distance [116]. The field of view which is the area at which the eyes can see is 135° vertical and 200° horizontal [117]. The eye is made up of three layers, the first or outer most layer consist of the cornea and sclera which constructs the shape of the eye. The second or middle later consist of the ciliary body, choroid, pigmented epithelium, lens, and iris. And the innermost layer consists of the retina which obtains the oxygen from the choroid and the retinal vessels [118]. Light from the source enters the eye through the cornea, passes the convex shaped lens and forms the intended image on the retina.

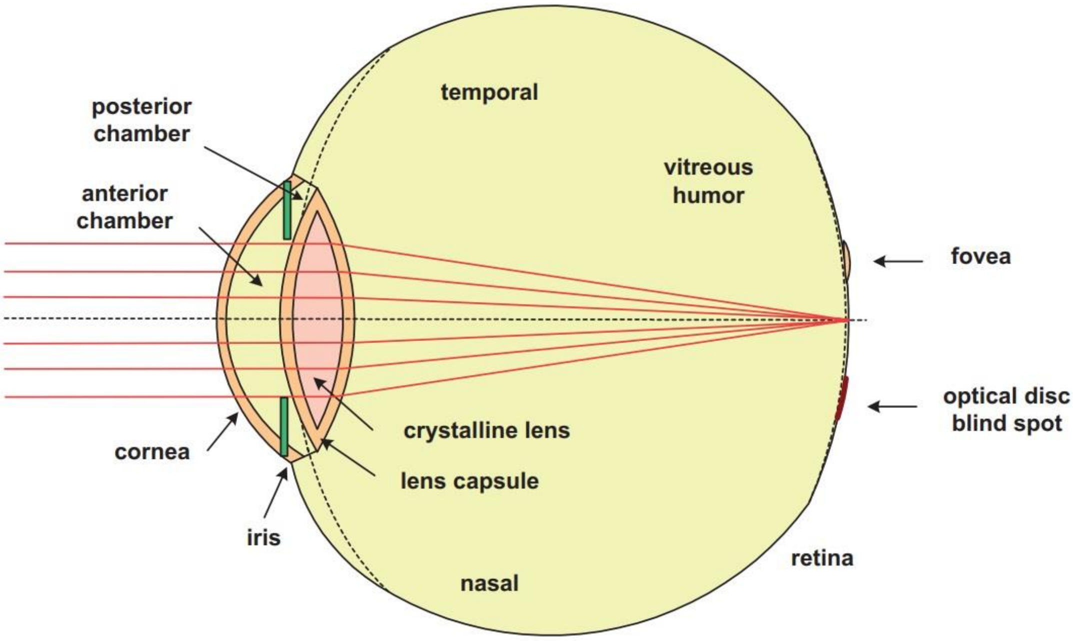

Figure 3. Schematic of the Human Eye [118]

At any point in time, the eyes can focus on an object at a distance about a range. This distance, however, might change consistently and the eyes need to change the focal distance to be able to view the object clearly. This ability is called accommodation [119]. The time needed to accommodate the eyes to change of focal length is different from individual and it can affect task performance when having the need to change focus between different planes. Research has shown that referencing to information situated on a different focal distance compared to the execution of task results in an increase in task completion time and higher error rate [120]. Besides information on a different focal plane, information out of the field of view can also affect the task performance [121].

Accommodation affects the comparison of optical see through and video see through AR. Optical see-through AR projects virtual objects at a parallel plane to the HMD, which is often different from the plane of the environment of task execution. As compared to video see through AR which the virtual objects are already projected onto the same plane as the environment. This difference of plane occurrence happens during the traditional manual method too, for example, using an instruction manual situation on a different area and referencing it while performing a task. Although the final projection of video see through AR may affect the depth perception of the user, the user might be able to process the given information at a faster rate with a reduction of error. Especially task where the movement when executing task is kept at a suitable margin, the depth perception problem will not be a factor when using video see through AR.

4.2 The Human Cognition

The human brain processes information and sends out signals to react appropriately. There are currently different methods to study how the human brain processes information. One framework is the adaptive control of thought-rational (ACT-R) [122]. ACT-R is a cognitive architecture. It studies how the human brain organises information and the reaction to produce what we term as intelligent behaviour. The current research of ACT-R is able to simulate and perceive a large range of cognitive tasks. There are different studies and framework available and no one research can fully depict and predict any cognitive task. In this chapter, ACT-R will be used as a reference to further understand the human brain.

Knowledge in ACT-R is categorised into 2 types. Chunks which are a series of declarative knowledge which contains facts and productions which are procedural knowledge that we display in our behaviour [123]. An example of a chunk is the addition of numbers that are definitive, and examples of procedural knowledge include conditions (IF ELSE) and logic that help formulate knowledge from a given set of knowledge. The ACT-R architecture is made up of a set of modules. The modules are namely goal module, declarative module, and procedural module. The goal module is to contain the current information needed to perform the current task. The declarative module contains information of the knowledge and facts learnt through understanding and memory. And lastly, the procedural module holds the procedural knowledge and constantly search for a suitable condition to execute actions and reactions [123]. The modules perform a unique cognitive function and are independent of other modules. Each module communicates with a buffer, each module may have different buffers that have its usage with communicate with other modules. An overall basic ACT-R architecture is shown below with. The rectangles represent modules, and the ovals represent the buffers. The blue arrows indicate reading of information from buffers to modules and the red arrows indicate making request from the modules to the buffers.

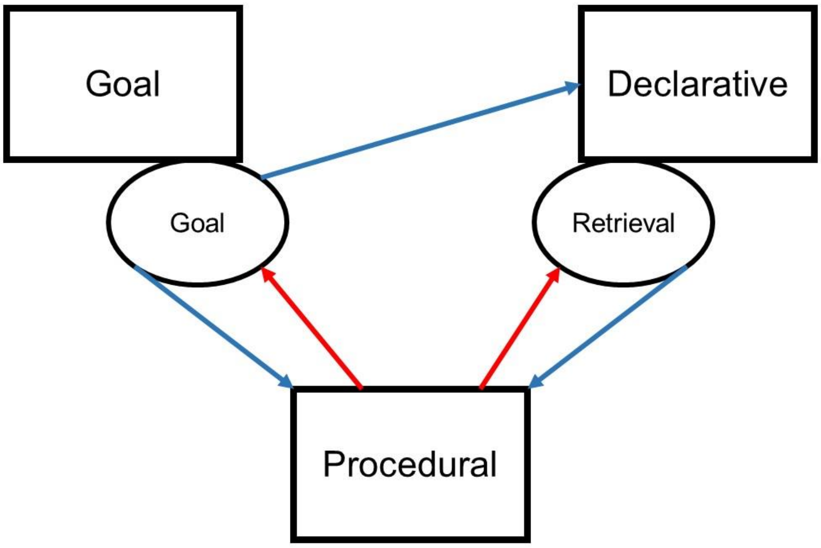

Figure 4. Basic ACT-R Architecture

Putting it in a simple example, we will use the example of solving a simple arithmetic equation: "What is 1+2?"

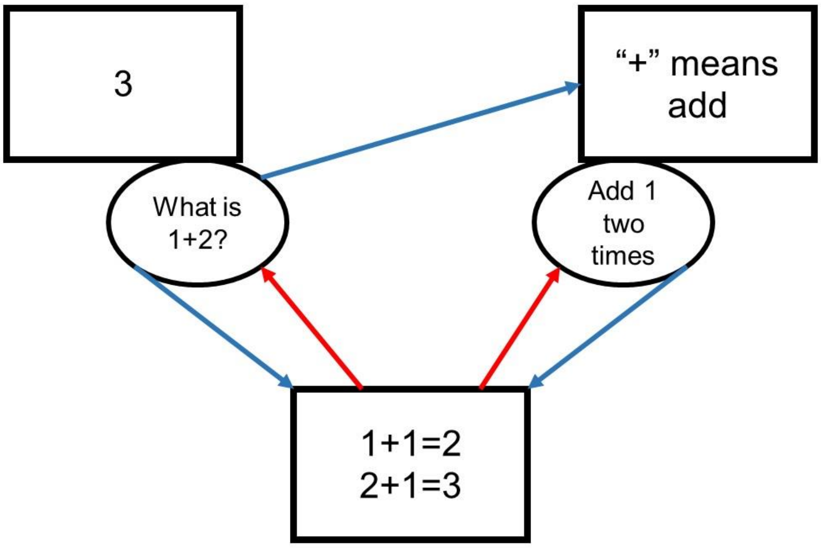

Figure 5. Simple Example of Implementing ACT-R Architecture

The goal buffer first sends the equation to the declarative module to search for the required knowledge needed; the symbol of "+" meaning addition. The retrieval buffer then holds the meaning of addition. The procedural module then sends a request to get the information from the retrieval buffer and proceeds to add the numbers together. Then it sends a request to the goal buffer to check whether the final goal is met. When the final goal is met which is the answer "3" the architecture completes. This example is only a simple overview, and the steps can be broken down into further components.

Ultimately, the most important point to take away from this theory is, human cognition derived by ACT-R is similar to that of a computer where information is stored at its relevant storage and being used when appropriate. The computation of information is also procedural which happens one at a time. This concept can be used to describe the process of information used when performing a task while using VR or AR devices.

When the user interacts with the information in order to complete with the given task, the user has to take the focus from the given task away and focus on the information. This phenomenon is otherwise known as task switching. Task switching requires users to spend cognitive processes to switch its focus from given task to another task. This will generally incur an increased task completion time overall and an increase in error [124]. Which is why contrary to popular belief, multitasking affects productivity negatively instead of making someone more productive.

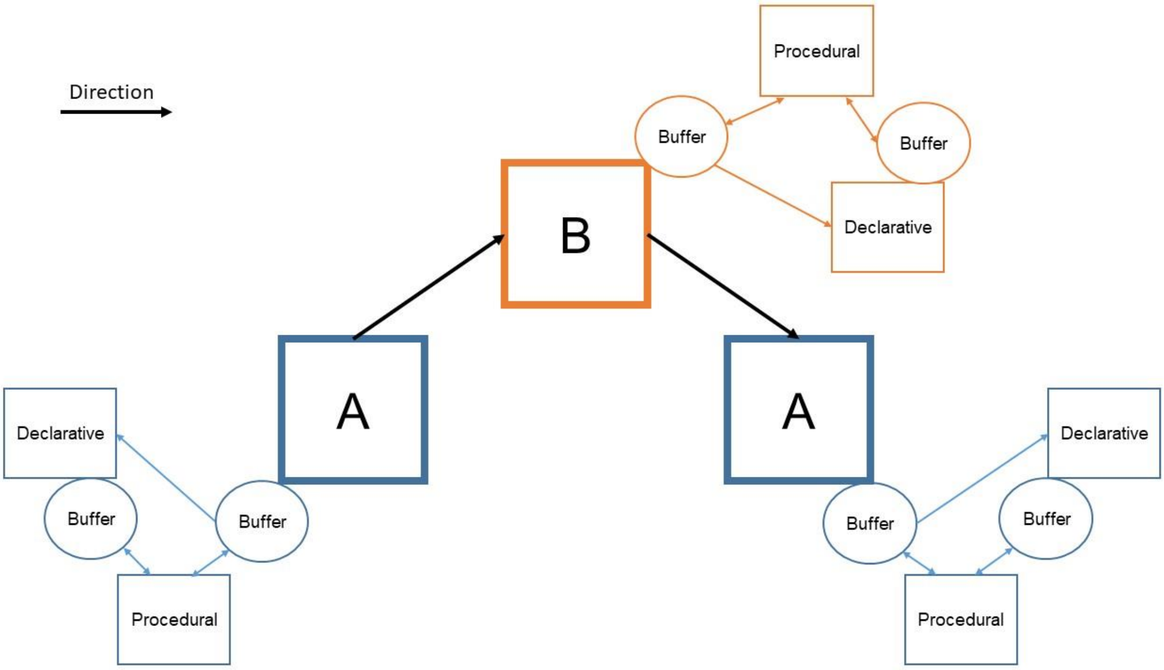

Figure 6. Sample Task Switching Architecture

As shown, when the user moves from task A to task B, the whole process of defining the buffers restart for the given task and this results in cognitive processing being spent. Besides changing of task, other forms of action such as the need to change in medium counts too as the cognitive processing needs to send the required signals to the eyes. Putting into context of AR, optical see-through headsets have the disadvantage as users have to spend cognitive processes to for the eyes to accommodate. A change from the real environment and to the virtual information and back to the real environment is needed too. The cost in visual processing results in a negative impact in the performance when using optical see-through AR as an aid for task completion instead [125]. As compared to video see-through AR, the real environment is being passed through as a medium equal to the information. This makes video see-through AR more superior theoretically when using it as an aid for task completion.

This chapter presents some concepts to further understand humans and how we operate. In summary, the eyes are the first organ to be exposed to VR and AR's virtual information. The individual's ability to receive accept the light projected by the virtual information and process these virtual information affects how the individual performance when using VR or AR applications. Looking upon how human operates cognitively, humans operate in blocks or chunks and information are processed procedurally. This breaks down on how users will process the information displayed by VR or AR. As humans are complicated in nature, the concepts might not be representative to everyone and is definitely different from each individual. There are key points in this chapter to take away in regard to AR devices. With the need for the eyes to accommodate to a change in plane, it makes reading of information from video see-through AR faster than optical see-through AR. In addition, as the user needs to result in cognitive processing due to a change in plane or even a change in medium, again, video see-through AR will be more superior than optical see-through AR.

Chapter 5: Video See Through AR Experiment

Chapter 3 and 4 allows us to understand the mechanics and capabilities of VR and AR and how the user using the technology reacts with this technology. In this chapter, an experiment will be performed on the use of video see-through AR to further understand the capacities of the device. The purpose of this experiment is to answer some of the hypotheses formulated from the researched performed:

1. ***How accessible is AR and how convenient it is to implement it in the workplace?***

   Most of the AR display devices are currently very niche and they can only perform the given task when implemented. The devices in the market are also not cost friendly which deters industrial application. As commercial companies are able to convert our everyday devices (cell phones and tablets) into video see through devices, are these devices capable enough to aid in task completion?

2. ***Will video see through AR make the user more efficient when performing a tabletop task with minimal movement?***

   Despite video see through AR will cause depth perception issues, some of the studies have pointed out that if the task given has distance that are within a certain margin, the effects of a reduction of depth perception might be redundant. In addition, ACT-R has shown that a change in media when processing information will result in cognitive processing. Therefore, in theory, when using video see through AR to perform a tabletop task, the user will have an improved task performance either in time or in the accuracy of the task performed.

5.1 Experiment Methodology and Setup

5.1.1 Pigpen Cipher

Most research work done utilizes different tasks to compare and assess the potential of introducing AR into a current situation. However, most tasks are niche, require a degree of background knowledge or resulting knowledge which will result in additional factors affecting the results. For example, fixing a toy car which have parts already known to be at specific positions or games whereby gamers will naturally excel in. Therefore, this disrupts the assessment of the performance of the AR device.

The task chosen for this experiment is a simple encoding and decoding cipher which matches shapes with the corresponding alphabet. The most original form of a Pigpen Cipher [126] is as shown.

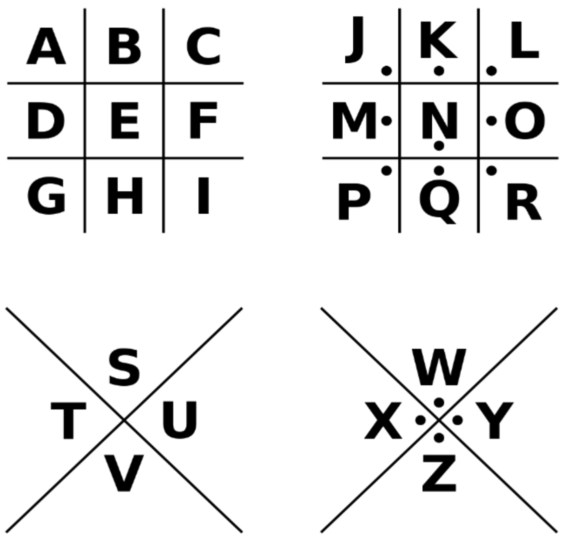

Figure 7. Pigpen Cipher [126]

For this experiment, the alphabets in the Pigpen Cipher will be randomized after each exercise to prevent memorizing of the shape corresponding to the alphabet.

Decoding and Encoding with randomizing the alphabets results in 2 different forms of assessment. Since the shape of the Pigpen Cipher will not change, in addition to the repetitive and understanding of the exercise; the decoding segment of the experiment will be a test of locating for information at a known position at a given space. An illustration can be shown below.

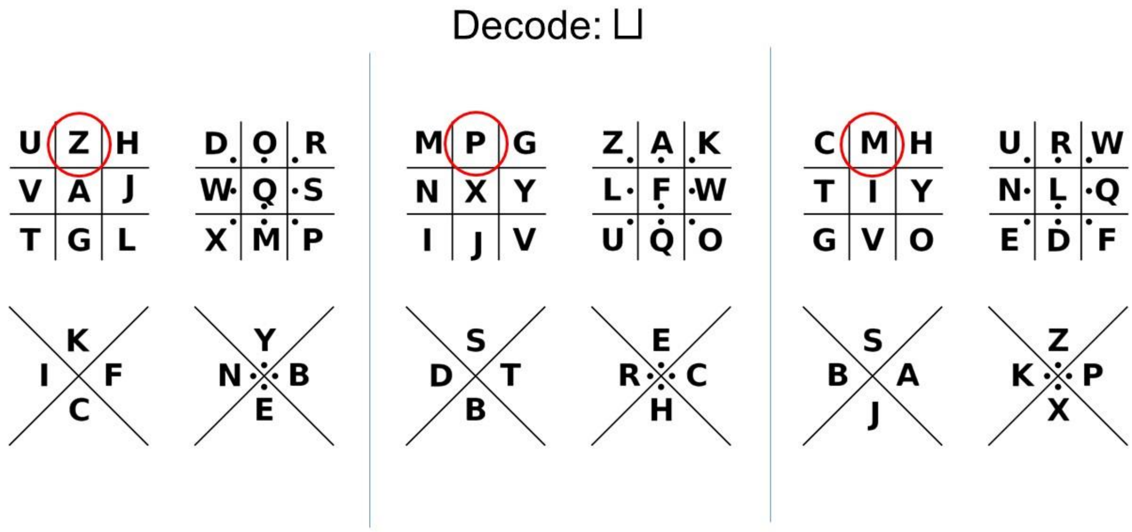

Figure 8. Example of Decoding Pigpen Cipher

In contrast, randomizing the position of the Pigpen Cipher will result in the encoding segment to be a test of locating for information at an unknown position in a given space. Similarly, an illustration can be shown below.

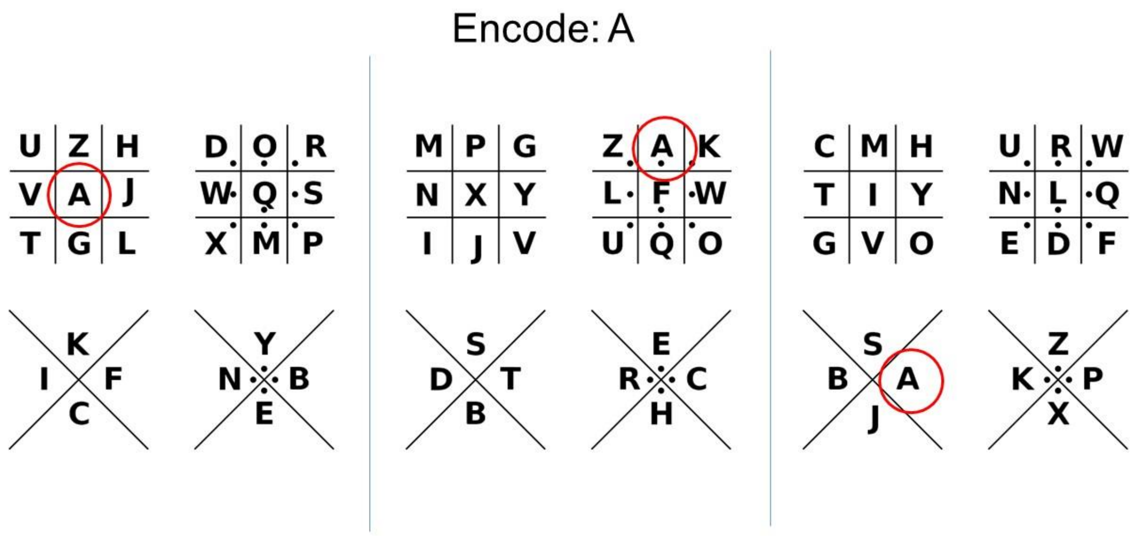

Figure 9 Example of Encoding Pigpen Cipher

5.1.2 Experiment Setup

The device used in this experiment are:

a. Tablet which portrays virtual information and the norm of referring to information in the modern era.

b. Tablet AR which uses the tablet as a form of AR display device, a convenient way to deploy AR application.

c. HMD in the form of a mobile device (Samsung Galaxy S10+) and Samsung Galaxy Gear, another convenient form of deploying AR applications due to the masses owning a state-of-the-art mobile phone.

Figure 10. Setup with Tablet (Left), Setup with Tablet AR (Middle), Setup with HMD (Right)

The AR applications are created with Unity [127] with added Vuforia SDK [128] for marker tracking.

The experiment setup is a static tabletop setup that require no movement of the body, and only requires the participant to write. Legible scribbling is also counted as the purpose is the purpose of the experiment is to complete the task quickly and accurately and not focused on aesthetics.

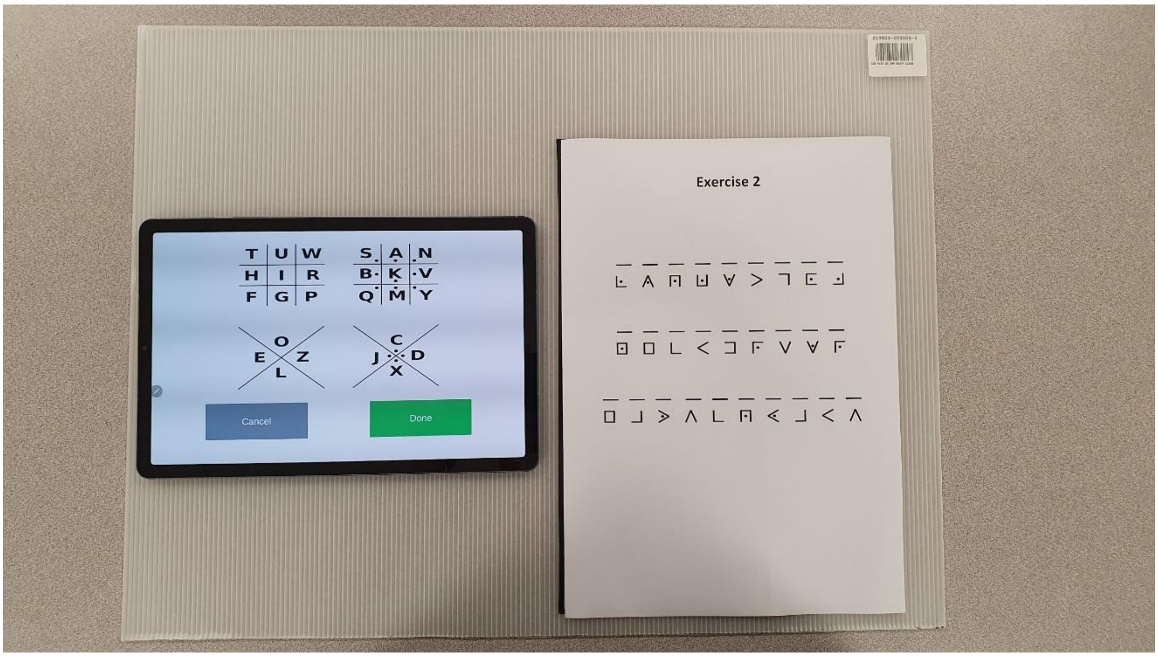

Figure 11. Workspace of the Experiment

The human performance parameters to be collected are:

1. Time - How fast the participant completes the experiment.
2. Accuracy - Number of mistakes the participant made, both actually making mistakes and/or self-correction.
3. Modified NASA-TLX questionnaire where the participants grade the Mental Demand, Performance, Effort and Frustration.
4. Qualitative questions while using the respective devices.
5. Arousal Level using a Galvanic Skin Response Sensor.

5.2 Experiment Procedure

20 participants of which 11 are males and 9 are females were chosen to perform the experiment. The age range of the participants fall between 22-36 and they are all personnel from the laboratory. 4 of which do not require spectacle aid and the rest are bespectacled. The experiments were conducted under a safe environment and Covid-19 regulations were adhered throughout the conduct of experiments. The data and safety of the participants are also adhered and approved according to National University of Singapore Institutional Review Board application (Annex A).

After each participant is being briefed on the experiment procedure, they will first learn the rules of Pigpen Cipher. A short worksheet is given to the participant to practice the decoding procedure using a traditional paper form of displaying information. After the participant is comfortable with the rules of Pigpen Cipher, they will proceed on the different display devices on at random. Throughout the experiment, they will be prompt to wear a galvanic skin response sensor on the left hand's middle finger and ring finger.

Figure 12 Example of Wearing the GSR

The experiment using a device is as follows:

1. There are 6 different exercises to be done, 3 encoding exercise and 3 decoding exercises within a display device. The application will guide them on which exercise to do next and what to expect for the experiment.

2. An exercise consist of a random pigpen cipher combination and an exercise worksheet to be filled up which the questions are randomly generated too.

3. After the participants are done with a display device, they are to take a 10minutes break before

starting on the other display devices.

4. The time taken to complete each exercise will be recorded by the device itself and the galvanic skin response will measure their amount of arousal while the participants are performing the experiment. The accuracy of the experiment will be done post experiment by the experimenter.

After the participant completes all 3 devices, the participant will conclude with filling up the modified NASA-TLX questionnaire and the additional qualitative questions on their opinions when performing the experiment (Annex B).

5.3 Experiment Results

An analysis was performed between all 3 devices comparing with each other i.e., Tablet vs Tablet AR, Tablet vs HMD, Tablet AR vs HMD. As the data collected were non-parametric, Wilcoxon signed-rank test [129] was used to evaluate the data. The significance for the data was set at $p < 0.05$ and the corresponding statistics value is 60. The coding language Python with the library Scipy.org [130] was used to compute the data.

5.3.1 NASA-TLX and Questionnaire

The NASA-TLX and questionnaire answers are explained first as the participants' qualitative feedback will help explain the reason for the other human performance parameters.

Table 3. Tablet vs Tablet AR Nasa-TLX Results

Tablet VS Tablet AR NASA-TLX			
Factor	**Statistics Value**	**p-value**	**Verdict**
Mental Demand	40	0.01458	Tablet uses less mental demand than Tablet AR
Performance	34	0.07348	Tablet has a higher performance than Tablet AR
Effort	37	0.00333	Tablet uses less effort than Tablet AR
Frustration	31	0.00297	Tablet has less frustration than Tablet AR

Table 4. Tablet vs HMD NASA-TLX Results

Tablet VS HMD NASA-TLX			
Factor	**Statistics Value**	**p-value**	**Verdict**
Mental Demand	40.5	0.00291	Tablet uses less mental demand than HMD
Performance	0	0.00018	Tablet has a higher performance than HMD
Effort	17	0.00022	Tablet uses less effort than HMD
Frustration	20.5	0.00000	Tablet has less frustration than HMD

Table 5. Tablet AR vs HMD NASA-TLX Results

Tablet AR VS HMD NASA-TLX			
Factor	**Statistics Value**	**p-value**	**Verdict**
Mental Demand	50	0.01216	Tablet AR uses less mental demand than HMD
Performance	15	0.00189	Tablet AR has a higher performance than HMD
Effort	31.5	0.01818	Tablet AR uses less effort than HMD
Frustration	20.5	0.00736	Tablet AR has less frustration than HMD

As shown on the table above, Tablet is superior to the Tablet AR and HMD. Tablet AR is much superior to HMD correspondingly. Making tablet ranked first as compared to the other AR devices. Gathering more of the qualitative findings from the participants, the participants felt that the tablet has the most familiarity as compared to the AR devices which is why they ranked Tablet much higher. The ergonomics and the tablet were also more comfortable and familiar to the participants compared to the virtual buttons of the AR devices. However, the participants highlighted that light intensity from the Tablet is different from the actual environment, making continuous switching from the Tablet to the physical worksheet straining for the eyes.

The Tablet AR garnered positive comments on having the eyes receiving the same light intensity, thus making reading information more comfortable than of Tablet AR. As the Tablet AR results in the end field of view to be smaller, the participants need not move their head as much. The lack of depth perception caused some of the participants who are particular on writing neatly to become uncomfortable. As the Tablet AR has a lower limit of which it can be placed close to the worksheet, some of the participants who have a shorter arm and torso might have the Tablet AR too close to the face, making them uncomfortable. Not all participants are able to get used to the new set up and new controls of the virtual buttons which results confusion while doing the experiment at first.

HMD received comments similar to the literature of the lack of distractions due to a reduction of the peripherals. However, as the Samsung Gear has a magnifying convex glass internally to attempt to make the experience 3D, it distorts the words on the screen, making the words illegible or makes similar letters for example, “O” and “Q” look alike. In addition, participants who wore glasses which are concave will experience a reduction of the correction of myopia. Similarly, the depth perception problem affects a large number of participants. For a number of participants, there will be heat generated from the pads of the Samsung Gear which caused irritation, some of the participants also experience discomfort due to the weight because of their natural sitting position.

Overall, the participants felt more comfortable using the Tablet as they are used to using it in the everyday lives. However, as the participants are young and tech savvy, they expressed interest in using the AR devices and an interesting experience despite some of the dissatisfaction. In addition, some of the aspects of the device received two sides of the comments. For example, although most participants felt that the reduction of peripherals helped them in becoming focused, two participants felt otherwise of being claustrophobic and uncomfortable. A question on what devices is preferred if the device were to be implemented on the workplace. 6 of them chose Tablet, 6 of them chose Tablet AR, 6 of them sat on the fence between Tablet and Tablet AR, and 2 of them chose HMD. The human performance parameters were reconsolidated to their individual groupings to see whether the interest affects the human performance but there are no significant changes compared to evaluating as the whole population.

5.3.2 Time

Table 6. Tablet vs Tablet AR Time Results

Tablet VS Tablet AR Time			
Exercise	**Statistics Value**	**p-value**	**Verdict**
Exercise 1	60	0.01051	Tablet is Less than Tablet AR
Exercise 2	6	0.00000	Tablet is Less than Tablet AR
Exercise 3	20	0.00000	Tablet is Less than Tablet AR
Exercise 4	92	0.10109	No Significant Difference
Exercise 5	56	0.00489	Tablet AR is Less than Tablet
Exercise 6	31	0.00028	Tablet is Less than Tablet AR

Table 7. Tablet vs HMD Time Results

Tablet VS HMD Time			
Exercise	**Statistics Value**	**p-value**	**Verdict**
Exercise 1	5	0.00000	Tablet is Less than HMD
Exercise 2	8	0.00000	Tablet is Less than HMD
Exercise 3	8	0.00000	Tablet is Less than HMD
Exercise 4	46	0.00200	HMD is Less than Tablet
Exercise 5	8	0.00000	Tablet is Less than HMD
Exercise 6	0	0.00000	Tablet is Less than HMD

Table 8. Tablet AR vs HMD Time Results

Tablet AR VS HMD Time			
Exercise	**Statistics Value**	**p-value**	**Verdict**
Exercise 1	55	0.03152	Tablet AR is Less than HMD
Exercise 2	53	0.00434	Tablet AR is Less than HMD
Exercise 3	58	0.01791	Tablet AR is Less than HMD
Exercise 4	54	0.01263	Tablet AR is Less than HMD
Exercise 5	38	0.00074	Tablet AR is Less than HMD
Exercise 6	39	0.00000	Tablet AR is Less than HMD

Looking at the results of the comparison, using the Tablet is the fastest, followed by Tablet AR then the slowest being HMD. This is highly probable as the participants are very familiar with the device and thus, they are able to operate the controls easier. Despite having the move their head more as the field of view for using the Tablet is larger, they are used to the motion. The lag of pressing the complete button due to unfamiliarity might affect the overall time too.

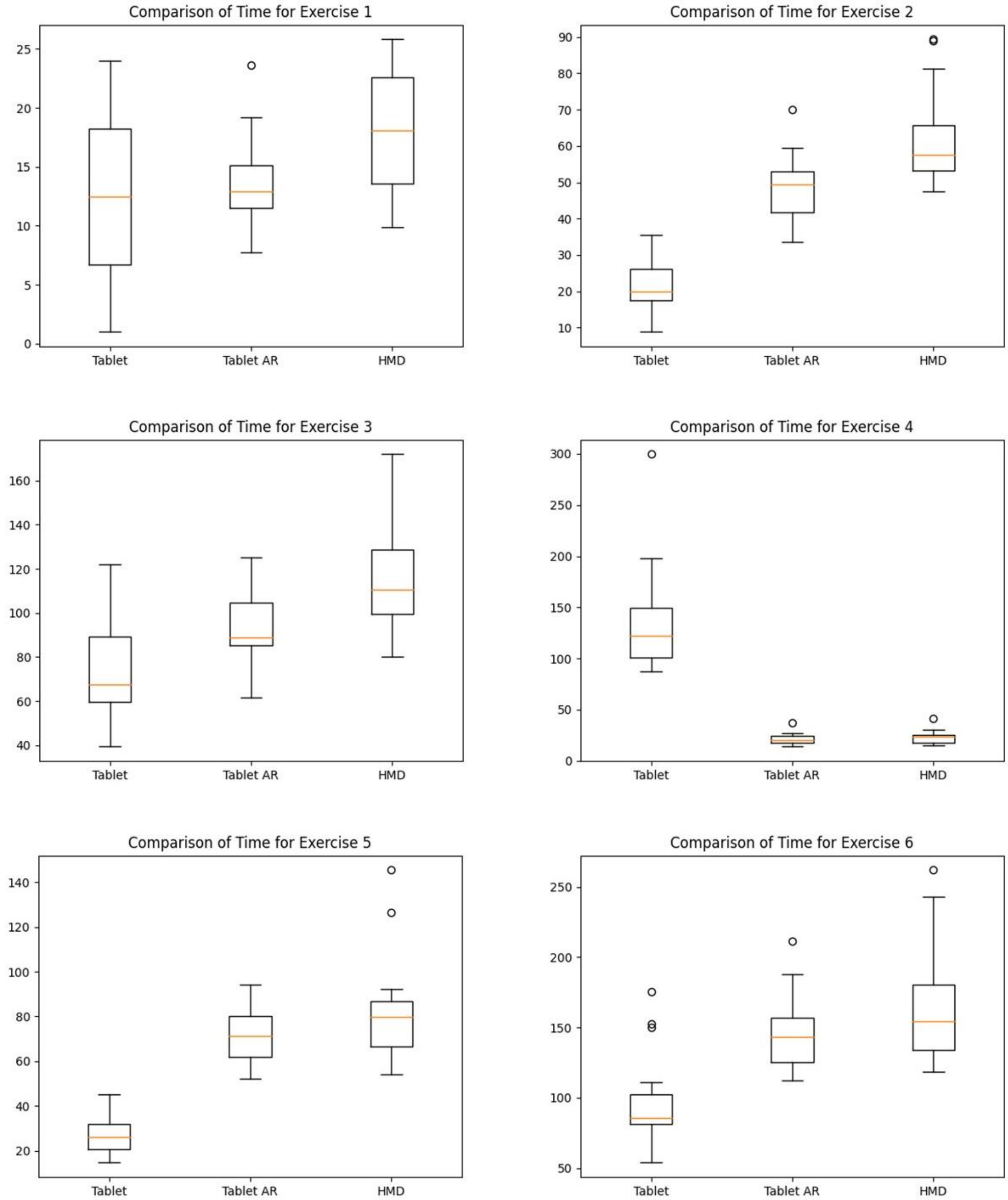

Figure 13. Box Plots for Time

Looking on the boxplots for the different experiments, it shows that for shorter exercises i.e., Exercise 1 & 4, the AR devices perform seemingly equal or better than the Tablet device. And for the longer experiments, the Tablet Device perform better. This could be due to fatigue of using the HMD due to the need to strain the eyes to read. Or it could be due to the fatigue from learning how to use the Tablet AR device as it was a totally new experience for them.

In summary, using the AR devices did not enable the participants to perform faster than using the traditional Tablet device. This is due to the lack of familiarity of the device which enables a slow control or fatigue in order to consistently remind themselves on how to use the device. Most of the participants did feedback on the lack of depth perception that slowed them down as it is harder for them to write. There are also a handful of participants who feedback that they have no problem writing despite the lack of depth perception. These give an insight and further understanding on how to tweak the experiment in the future in order to properly validate and evaluate AR devices.

5.3.3 Accuracy

Besides studying the mistakes made, the number of times the subject changed the answer was evaluated to find out more on how the AR devices might affect the performance of the participants. The actual mistakes were termed as "Actual Mistakes" and the ones that that subject changed due a lapse in memory or other similar instances are termed "Self Mistakes". The given task is very simple and thus, not all participants made mistakes which affect the evaluation of data using Wilcoxon thus this result to a very small size if the only the participants who made an error was evaluated. Thus, the mean and the number of participants made mistakes were used to evaluate instead. The highest value was underlined.

Table 9. Mean Accuracy for All Devices

Mean Mistakes **Legend: (<u>Highest Value</u>)**						
	Tablet		**Tablet AR**		**HMD**	
Exercise	**Actual Mistakes**	**Self Mistakes**	**Actual Mistakes**	**Self Mistakes**	**Actual Mistakes**	**Self Mistakes**
Exercise 1	0	0	<u>0.125</u>	<u>0.0417</u>	0.0833	<u>0.0417</u>
Exercise 2	0.167	0.208	0.333	0.0833	<u>0.458</u>	<u>0.25</u>
Exercise 3	0.0416	0.0833	<u>0.5</u>	<u>0.25</u>	0.25	<u>0.25</u>
Exercise 4	0	0.0417	0	0	<u>0.0417</u>	<u>0.1667</u>
Exercise 5	0.0417	0.0833	0	<u>0.125</u>	<u>0.125</u>	<u>0.125</u>
Exercise 6	0.0417	0.417	0	0.25	<u>0.417</u>	<u>0.458</u>

Table 10. Number of Participants for Accuracy

Number of Participants Making Mistakes **Legend: (<u>Highest Value</u>)**						
	Tablet		**Tablet AR**		**HMD**	
Exercise	**Actual Mistakes**	**Self Mistakes**	**Actual Mistakes**	**Self Mistakes**	**Actual Mistakes**	**Self Mistakes**
Exercise 1	0	0	<u>2</u>	<u>1</u>	<u>2</u>	<u>1</u>
Exercise 2	3	4	4	2	<u>7</u>	<u>5</u>
Exercise 3	1	<u>7</u>	<u>5</u>	6	<u>5</u>	5
Exercise 4	1	1	0	0	<u>4</u>	<u>2</u>
Exercise 5	1	2	0	<u>3</u>	<u>2</u>	<u>3</u>
Exercise 6	1	4	0	6	<u>5</u>	<u>8</u>

Overall, HMD has the most errors for all exercises in in terms of actual mistakes and self mistakes. Between Tablet and Tablet AR, Tablet AR has more actual mistakes and self mistakes for decoding exercises (Exercise 1, 2, 3). Tablet has more actual mistakes and self mistakes for encoding exercises (Exercise 4, 5, 6).

The reason for the mistakes occurring can be inferred from the feedback by the participants and the observations during the experiment. For the HMD, the resolution was unclear for the participants as feedbacked by them. This results in mistakes regarding similar letters. Using the Tablet during the decoding exercises often results in mistakes either Actual or Self when the subject reads off an adjacent spot instead of the actual. This could be due to a lack of feedback to confirm the reading of information as the worksheet and the Tablet is not within the same field of view or could be due to a lack of concentration when performing the experiment due to familiarity i.e., complacency arises. For the AR devices, the lack of depth perception results in the participants to write messily and this bothered some of the participants, causing them to rewrite the letters and symbols thus contributing to the Self Mistakes.

The experiment proves that utilising AR devices might result in a reduction in errors made. This is especially so for the Tablet AR especially for encoding exercises which mimic real life searching for information. However, using Tablet AR has more Actual Mistakes on the decoding exercises which might stem from unfamiliarity of using the device as a whole which many participants pointed out that they underestimated themselves and actually am unfamiliar with the device despite the explanations and having to try out the controls beforehand.

5.3.4 GSR Values

The mean GSR values while performing the individual exercise were used to evaluate. Every subject starts off with a different value and also the change cannot be compared from subject to subject but only relative to the own subject. The mean obtained is being ranked with 1 being the lowest obtained and 3 being the highest obtained value. The results are as shown below.

Table 11 Tablet vs Tablet AR GSR Results

Tablet VS Tablet AR GSR Values			
Exercise	**Statistics Value**	**p-value**	**Verdict**
Exercise 1	120	0.40611	No Significant Difference
Exercise 2	92	0.90168	No Significant Difference
Exercise 3	114	0.44247	No Significant Difference
Exercise 4	121.5	0.60627	No Significant Difference
Exercise 5	146	0.92181	No Significant Difference
Exercise 6	138	0.74693	No Significant Difference

Table 12 Tablet vs HMD GSR Results

Tablet VS HMD GSR Values			
Exercise	**Statistics Value**	**p-value**	**Verdict**
Exercise 1	147.5	0.96643	No Significant Difference
Exercise 2	89	0.08492	No Significant Difference
Exercise 3	55	0.00533	Tablet Less than HMD
Exercise 4	101	0.16881	No Significant Difference
Exercise 5	114.5	0.31651	No Significant Difference
Exercise 6	85	0.09236	No Significant Difference

Table 13 Tablet AR vs HMD GSR Results

Tablet AR VS HMD GSR Values			
Exercise	**Statistics Value**	**p-value**	**Verdict**
Exercise 1	120.5	0.58278	No Significant Difference
Exercise 2	59.5	0.02707	Tablet AR Less than HMD
Exercise 3	60.5	0.01509	Tablet AR Less than HMD
Exercise 4	74.5	0.03686	Tablet AR Less than HMD
Exercise 5	108.5	0.34038	No Significant Difference
Exercise 6	107.5	0.22919	No Significant Difference

GSR values shows no significant difference for Tablet vs Tablet AR across all exercises. No significant difference for Tablet vs HMD for all exercises except exercise 3 with Tablet having less than HMD. For Tablet AR vs HMD, Exercises 2, 3, 4 showed that GSR value of Tablet AR is less than HMD. Overall, the results cannot come to a concrete conclusion on which device is superior to the other. This is because of the nature of GSR data being relative to only the user. The change and the initial GSR value will be different from user to user and there are so many factors causing a change in GSR levels such as movement and emotional state. There could be possible reasons of explaining the reason for Tablet AR vs HMD, with HMD having a higher value i.e., more aroused. The uncomfortable aspect of using the HMD results the participants to be more engaged such as having the need to concentrate on reading the unclear words or just the ergonomic aspects.

Using the GSR in this experiment proves no contribution to the findings of any. The GSR was trial in this experiment to find out whether this device was suitable for evaluation of human performance. However, as the nature of the GSR was already stated, it should be used to compare different task execution and compared within each individual. Nonetheless, it was a learning experience operating and understanding the GSR.

5.4 Discussion of Experiment

In summary, the experiment conducted did not show a definitive positive result of using AR devices being more superior than using the traditional method. This could be due to various reasons such as the participants being not familiar with the AR devices despite being explained on the control of the devices and having the participants test out the devices before actually starting on the experiment. The nature of the task needs changes too as the task might be too mundane for the participants to perform in the long run, causing some of the participants to treat the experiment differently for the different length of the experiments. Some of the participants enjoyed doing the given task which affects their speed and consistency of using the devices. This will affect the accuracy and the time to complete the experiment. Nonetheless, every task has its corresponding issue, and it is not easy to find a general task to evaluate the performance of the AR devices. In summary for this experiment, the Tablet AR showed that it can perform the closest performance as compared to the traditional Tablet. This shows that an AR modified everyday device might be suitable in a non-critical tabletop task. In addition, the performance of said AR display devices could prove to be more efficient in improving human performance in a suitable environment, task, or the preference of the user. In order to further compare the devices, the quality of the devices needs to be enhanced such as changing the Samsung Gear to a better quality. The Samsung Gear is currently a 2016 model which is still Samsung's first time creating such a device. The attempted addition of the convex glass proves to be unsuccessful in enhancing the experience of the HMD. The given task could be modified or performed on an actual task to better evaluate the AR devices for the given scenario. Overall, it was a learning experience in learning how to develop an AR application and learning how to implement basic text instructions to display to the users. The participants themselves learnt more on the capabilities of an AR device too as most of them did not have experience of actually handle an AR device outside of the gaming purpose. As the experiment was conducted during a pandemic situation, some of the added precautions may affect the overall experience when performing the experiment too. One example is that wearing mask results in participants not receptive to wearing additional equipment on their head which in turn making HMD not very receptive to the participants.

Besides learning on the AR technology, the experiment showed that the user will affect the overall human performance when given the technology. Factors such as preference, background knowledge and dexterity affect the results when using AR devices. As mentioned in Chapter 3 and Chapter 4, hand eye coordination is an important fine motor skill for task completion. Although this experiment did not find out on the difference of hand eye coordination and its effect on the usage of video see-through AR, it naturally got raised by the participants. Depth perception capability naturally affects the hand eye coordination of the person. A person who has good hand eye coordination will have better depth perception [131] and vice versa [132]. The participants can be narrowed or separated according to a defined level of hand eye coordination level. They can be assessed with secondary task skills [53] or even EEG methods [56]. As video see-through AR's biggest issue which affects other performance parameters is the depth perception, having participants with a good level of hand eye coordination might result in a different set of results when evaluating human performance parameters while using this technology.

Chapter 6: Conclusions and Future Work

The objective of this research is to investigate the capabilities of VR and AR and how to improve the evaluation of these technologies and achieve widespread deployment of this technology in industries. This study focuses on understanding the different modes of AR display methods which are optical see-through and video see-through display modes. The common human performance factors are also discussed and how to access them in terms of time, accuracy, cognitive load and also a fine motor skill, hand eye coordination. Currently, the common industries namely medical training, surgical operation and also in the engineering workplace highly benefitted from the use of VR and AR. This is due to the main usage of this technology which is to provide additional information to guide workers in these information heavy fields. In addition, different environments can be simulated in order to provide and enhance the learning process for the junior medical and engineering professionals. Besides learning about the technology, human factors are also discussed to find out more reasons on the success of implementing VR and AR. An experiment on the use of video see-through AR at a basic level is also performed to understand more on how industrialisation of AR technology can be worked towards to. Although, strong positive results could not be found in regard to human performance measures, the human performance parameters are comparable for the comparison between the traditional Tablet method and an enhanced Tablet AR method. More insights are found out while conducting this experiment too. From the experiment, human factors can be seen as they play a large role in the success of implementing this technology such as emotions and biasness when using the technology. The experiences with using the technology and fine motor skills affect the usage too. The nature of the task also determine the success of the implementation.

The implementation of VR and AR into the workplace is still lacking due to the capabilities of the technology. More exposure is needed at an industrial level to allow researchers to gather more insight on the areas of development too. At the current situation, this technology is highly suitable for educational situations especially of those in the engineering or medical industries. This is because not all students have good 3D visualisation and spatial awareness. Pictures from literature and textbooks do not necessary describe the overall situation properly. Especially during situations such as a global pandemic at the time of writing this thesis, most of the students are currently learning from home. As such, they could not be exposed to on the job training or prototypes in their respective educational institutes. Having implementation of VR and AR will improve the overall learning experience of the student. On an operational scale, the most feasible implementation would be teleoperation of robots. Situations whereby it is not physically safe humans to be at the environment itself for example, diffusing a bomb or operating with contagious environment will benefit from this implementation. VR and AR will enhance the experience of controlling robots to ensure a higher success rate while teleoperating the robots needed for the situation. On the other hand, situations whereby it is still safe for humans to be physically at the scene still face ethical policy issues. In the event of a technological lapse for example, lag time of displaying critical information for surgeons which results in a mishap, it will be difficult to pinpoint and administer the appropriate aftermath actions.

Overall, there is still lack of a general framework of implementing this technology which comes to no surprise due to the many factors affecting the nature of the framework. Different tasks have different requirements for any form of implementation and the background of the user will affect the framework too. The best form of learning towards implementing the technology for a specific task is to understand the actual task and the user themselves. Ultimately, there is no best framework, only the right framework for the implementation of VR and AR at an industrial level.

6.1 Possible Research Area in Interventional Radiology

One such example of teleoperation using VR and AR would be interventional radiology. Interventional Radiology is a subspecialty of MIS procedure that uses medical image guidance to perform the surgical procedure. Medical images are taken during the surgical procedure with medical imaging technology such as x-ray fluoroscopy, magnetic resonance imaging or ultrasound [133]. This is different from the procedures in Chapter 3 where the images were taken before the surgical process. The motivation of this procedure is the images taken during the medical procedure will be more accurate of the current situation and partially due to the reduction of radiation exposure due to an upgrade in medical imaging technology [134]. However, this often results in medical professionals facing an overdose of radiation from the procedure. Overdose of radiation pose a critical problem to medical professionals such as increase chances of cancer risks, organ, and tissue problems [135]. Precautionary measures have been created to protect medical professionals such as radiative protective garments [136] or protocols to monitor and limit the amount of exposure being exposed for a period of time [137]. However, medical professionals still faced a relatively high amount of radiation exposure due to leakage from the protective garment or wear and tear [138]. Areas such as the eyes and hands are also practically hard to shield [139]. In addition, it is hard to regulate the amount of radiation exposure to each medical professional as it is hard to predict medical emergencies [137]. Wearing dosimeters around the body to monitor the amount of radiation is not a very practical solution too.

The future of AR and teleoperation of machines might be the solution to this problem. Similar to the teleoperation of robots in a dangerous environment, medical professionals will have the ability to control surgical robots remotely to mitigate radiation exposure [109] [140]. This is highly probable as the inclusion of surgical robots in the surgical room has proven success of higher accuracy due to the stability compared to human hands [70] [141]. Video see-through AR will be used in this situation which transmit the video live feed to the surgeon who is situation in another room. In addition, AR makes the control of the robots remotely natural compared to using traditional HMI controllers. Since controlling the robots remotely will be an instance of a video see through display, the surgeon controlling the surgical robot might face depth perception issues. However, this could be easily mitigated with good level of spatial awareness and hand eye coordination. Nonetheless, there are other areas of concern regarding this technology such as network issues and the training needed to ensure that surgeons are fully equip with the necessary skills. If everything can be accomplished, it will allow surgeons to perform interventional radiology on patients from a different room and not be exposed to the radiation from the medical imaging machines. Making interventional radiology more sustainable and safer for surgeons.

There is current non-surgical research done on the teleoperation of machines for medical professionals for the intention of treating and handling infectious environments. Teleoperation robotic arms can be used to allow medical professionals to handle patients or equipment from a different environment [142]. This is useful especially in environments such as handling Covid-19 pandemic situations. Current research on interventional radiology training [143] are also done to propose efficient training for medical professionals. More research on the creation of training, protocols and design of the technology needs to be done in order to make teleoperation of such robots feasible.

END

Publication List

J.-H. Yin, C.-B. Chng, P.-M. Wong, N. Ho, M. Chua, and C.-K. Chui, 'VR and AR in human performance research―An NUS experience', Virtual Reality & Intelligent Hardware, vol. 2, no. 5, pp. 381–393, Oct. 2020, doi: 10.1016/j.vrih.2020.07.009.

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Annex

Annex A: NUS-IRB-2020-762

Office of the Deputy President (Research and Technology)
Institutional Review Board

NUS National University of Singapore

NUS-IRB Reference Code: NUS-IRB-2020-762

5 January 2021

Mr Jun Hao Yin (Graduate Student)
Dept of Mechanical Engineering
Faculty of Engineering
National University of Singapore

Dear Mr Yin,

EXEMPTION FROM NUS INSTITUTIONAL REVIEW BOARD (NUS-IRB) REVIEW

Protocol Title: Comparison between Video See Through Augmented Reality Information with Tablet-Based Information

Principal Investigator: Mr Jun Hao Yin (Graduate Student)
Co-Investigator(s): Chee Kong Chui

Source of Funding: Nil

We are pleased to inform you that the NUS Institutional Review Board (NUS-IRB) has reviewed and approved the ethical aspects of your above-mentioned research based on your declaration and the IRB Application Form submitted.

We note that your research only involves human participants as stated in the following categories:

(2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behaviour, unless: (i) information obtained is recorded in such a manner that research participants can be identified, directly or through identifiers linked to the research participants; and (ii) any disclosure of the research participants' responses outside the research could reasonably place the research participants at risk of criminal or civil liability or be damaging to the research participants' financial standing, employability, or reputation.

(7B) Research involving benign behavioural interventions where disclosure of subjects' responses outside research would not reasonably place the subjects at risk.

The exemption shall remain valid until such time the research is completed, unless the research is terminated earlier for any reason whatsoever.

The NUS-IRB has reviewed the IRB application form and the following documents for the purpose of granting the exemption from NUS-IRB review: -

Documents

1. Survey Questions
2. Pictures Explanation

Please note that:

1. The Principal Investigator should inform the NUS-IRB within two (2) working days if any significant deviations from the information submitted in this application arise.

2. The Principal Investigator should apply for IRB approval if s/he decides to include any other human participants in the research at a later point in time.

3. The Principal Investigator should submit the Closure submission via iRIMS-IRB within 3 months after the completion of the research.

4. The Principal Investigator is responsible to inform the NUS-IRB should s/he tender resignation from NUS and notify us of any changes to the study status, e.g. change in Principal Investigator or study termination. Otherwise, the IRB approval will lapse 3 months from the date of your official departure from NUS.

5. All applicable forms/reports can be completed and submitted via the online system (iRIMS-IRB).

Thank you.

Yours sincerely,

Professor Saw Seang Mei
Deputy Co-Chair, Institutional Review Board
National University of Singapore

This is a system generated approval letter. No signature is required.

Block MD 11, #05-09, 10 Medical Drive, Singapore 117597
Tel: 65-6516 4311
Website: http://www.nus.edu.sg/research/irb
Company Registration No: 200604346E

Annex B: Experiment Questionnaire

Comparing Video See-Through AR with Tablet-Based Information Questionnaire

Age:

Date of Experiment:

Time of Experiment:

Tablet

Mental Demand – How mentally demanding was it to use the device?

1 2 3 4 5 6 7 8 9 10

Performance – How successful were you in accomplishing the task?

1 2 3 4 5 6 7 8 9 10

Effort – How hard did you have to work in accomplishing the task?

1 2 3 4 5 6 7 8 9 10

Frustration – How insecure, discourage, irritated and annoyed were you?

1 2 3 4 5 6 7 8 9 10

Tablet AR

Mental Demand – How mentally demanding was it to use the device?

1 2 3 4 5 6 7 8 9 10

Performance – How successful were you in accomplishing the task?

1 2 3 4 5 6 7 8 9 10

Effort – How hard did you have to work in accomplishing the task?

1 2 3 4 5 6 7 8 9 10

Frustration – How insecure, discourage, irritated and annoyed were you?

1 2 3 4 5 6 7 8 9 10

HMD

Mental Demand – How mentally demanding was it to use the device?

1 2 3 4 5 6 7 8 9 10

Performance – How successful were you in accomplishing the task?

1 2 3 4 5 6 7 8 9 10

Effort – How hard did you have to work in accomplishing the task?

1 2 3 4 5 6 7 8 9 10

Frustration – How insecure, discourage, irritated and annoyed were you?

1 2 3 4 5 6 7 8 9 10

Additional Questions

Which device do you feel the most comfortable in completing the task? And why?

Do you have any improvements in terms of the design of the task? E.g. interface, colours of the display.

Do you have any improvements in terms of the experiment? E.g. number of pigpen to encode/decode.