

ABSTRACT

Title of Thesis: EFFECTS OF AUGMENTED REALITY
BASED OBJECT ILLUMINATION ON
HUMAN PERFORMANCE

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Engineering

Extravehicular Activities (EVAs) in space are generally considered to be high-risk, costly activities, due to the nature of the working environment and the limitations imposed on astronaut mobility and dexterity. Procedures are scheduled out and rehearsed far in advance, with time being considered a precious commodity during missions. Providing artificial task guidance to astronauts could potentially improve their efficiency, enabling for shorter duration EVAs and/or a larger quantity of tasks completed.

This research quantitatively measured the effects of virtually illuminating or “cueing” objects of interest on a user’s ability to complete a predefined task, through the use of augmented reality (AR) “active display” symbology. This was achieved through the

implementation of a Microsoft HoloLens™ head mounted display. It was demonstrated that, after controlling for a variety of factors, virtual illumination techniques improved task completion speed by approximately 100% and reduced perceived mental workload, with no adverse effects on accuracy.

EFFECTS OF AUGMENTED REALITY BASED OBJECT ILLUMINATION ON
HUMAN PERFORMANCE

by

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Dedication

This work is dedicated to my parents, whose guidance and support first set me on this path to becoming an engineer;

To my wife, whose love, support and patience has enabled me to excel in all that I endeavor to achieve;

And to my children, for whom I strive to be the example that I seek in life

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List of Abbreviations/Technical Definitions

AR Augmented Reality: A general term which here describes a means of supplementing a user’s visual perception of the world around them with computer generated text, symbology, or other means of information presentation.

AR Active Display: A method of displaying AR symbology which DOES interact directly or align with the real world workstation, from the user’s perspective (i.e. symbology overlaid onto a real-world object, which appears to remain “attached” to the object through a range of perspectives).

AR Static Display: A method of displaying AR symbology which DOES NOT directly interact or align with the real-world workstation, from the user’s perspective (i.e. a floating checklist, metrics, etc.).

HMD Head Mounted Display: A visual display system which is self-contained and resides solely on the user’s body, and presents visual imagery to the user.

Hologram: In this thesis, hologram is defined as the holographic image produced by the HoloLens and shown onto the display window. While the image appears 3-dimensional to the user, this is admittedly not a traditional hologram produced through the interference of laser light, directly into the real environment.

Microsoft HoloLens HMD: The HMD of choice for this study.

FOV Field of View: The total angular range in which a sensor or human eye can perceive information.

CAD Computer Aided Design: The process of developing a detailed digital model of an object.

Siemens NX11 CAD Software: The software of choice for modeling the physical pegboard test apparatus.

Unity Unity Real-Time Development Platform: The programming platform of choice for developing the HMD software for this study. Unity is a cross-platform game engine developed by Unity Technologies.

Vuforia MRTK Vuforia Mixed Reality Tool Kit: The Augmented Reality add-on software of choice for Unity.

Chapter 1: Scientific Rationale

1.1 Background

“Hands-on” task time in space is generally considered to be a valuable commodity. Astronauts typically train for a year or more before launching on a specific mission. Task time becomes especially significant during Extravehicular Activities (EVAs), where the risks to safety are significantly higher. This is coupled with the fact that basic maneuverability, dexterity and visibility are significantly reduced due to the nature of the spacesuit and the working environment.

Continuous ground support is required throughout the duration of each mission, and astronauts’ daily schedules are rigidly delineated in order to maximize their task completion efficiency. Even with this continuous support, Apollo astronauts routinely fell behind schedule and had to drop certain tasks in order to stay within the time limits for life support consumables [1].

It is proposed that implementing an augmented reality (AR) display into an astronaut’s spacesuit helmet could aid with object identification during an EVA activity, which could potentially allow the astronaut to complete individual EVA tasks more quickly and efficiently. This would help to reduce the abovementioned risks to safety, and increase the chances of mission success.

More broadly, AR seems to lend itself to tasks in which the user must manipulate multiple parts of a larger workstation in a complicated manner, such as for most in-situ repair and maintenance operations. For example:

- A maintainer replacing a piece of an aircraft might have to remove several access panels, each with multiple screws, in the proper order, unplug wires, disconnect fittings, etc., then reassemble everything in the reverse order. Every part that is being moved could have different starting and ending locations.
- An astronaut stationed at a lunar or Mars surface base may have to execute a similarly complex repair or replacement of hardware, with limited resources that may not be in their original designated locations.

Aside from maintenance and repair operations, the technology could theoretically lend itself to object identification and inventory tracking, both of which are not well represented by the Duplo Block test. For example:

- A user sitting at an extensive workstation might use an AR-based display method to monitor many gauges and operate multiple switches and dials, any one of which might require attention at any given time.
- A warehouse worker could use an AR-based display method to track down a package which is stored somewhere within a large building, by visually searching for a virtual “dog tag” of information.

Before any such technology is implemented in a real-world scenario, the effects of “virtual illumination” of real objects on user performance must be quantified. Here the term virtual illumination is defined as the technique of highlighting a specific real-world object of interest for the user, through the use of AR-based symbology which closely overlays the object from the user’s perspective.

1.2 Research Objectives

The objectives of this effort are two-fold:

- 1) Develop a robust test for evaluating and comparing the effects of various information presentation techniques on human performance.
- 2) Use this test to determine the effect of AR based virtual illumination of real objects on a user’s ability to complete a predetermined set of tasks, both within and outside of the head mounted display (HMD) field of view (FOV).

These objectives will be accomplished through the implementation of a novel test method, termed the Pegboard Test, utilizing a Microsoft HoloLens™ HMD to provide both virtual illumination of real objects and a virtual checklist to serve as a control. Here the term “virtual checklist” is defined as the technique of directing the user’s attention to objects of interest via the use of written instructions, which are presented to the user via the HMD. This information appears to the user as a stationary “page” of written information. HMD FOV is defined as the angular span of the display as presented to the user.

Of particular interest is the HMD's ability to draw a user's attention to objects that are outside of its FOV, through the use of on-screen targeting symbology that directs the user's attention toward the object of interest.

1.3 Hypothesis

Virtual illumination of real objects will draw a user's attention to those objects faster. Faster object identification will allow for faster and more precise task execution. This effect should be measurable as an increase in speed and accuracy.

Chapter 2: Previous Work

The goal of this research effort is to quantifiably compare information presentation techniques, referred to in this thesis as “display methods”. This research does not serve as an evaluation of any one particular piece or brand of hardware or software. Likewise, the focus of this literature review is not on the “stuff”, but rather on the “technique”; specifically, on human performance as it relates to various display methods.

Unfortunately, the current state of the literature in the public domain, as it pertains to truly fundamental comparison research between AR based information presentation and more traditional (i.e. paper based, tablet based) checklist information presentation, is lacking. With the advent of modern wearable AR technology such as the Microsoft HoloLens, Magic Leap One and Google Glass among others [2], the pace of technology development seems to have partially leapt over the fundamental science with regards to human performance integration with the technology. To be clear, many situation specific usage cases for AR exist in the literature, with accompanying research to determine its efficacy in those specific scenarios (2.2.2 Individualized / **Task-Specific Studies**). Additionally, the effects of specific aspects of an AR system on human response performance, such as focal distance or resolution, are generally well represented [3, 4]. However, the effect of AR on a non-situation specific discrete task, such as manipulating an object within a workstation, is less well understood.

2.1 Augmented Reality Defined

Although prior definitions for virtual reality (VR) and AR have existed and evolved over a number of years, Milgram, *et al.* [5], first defined the Reality-Virtuality Continuum as a range of perceived realities upon which AR and VR are found (1).

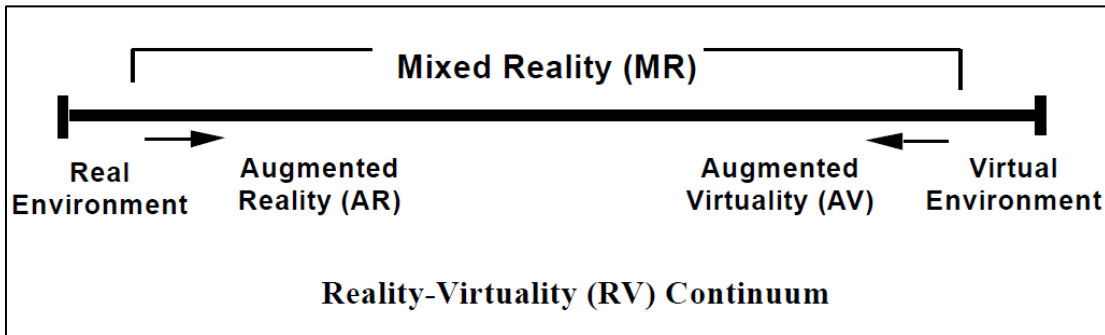


Figure 1: Reality-Virtuality Continuum as first proposed by Milgram, *et al.* [3]

At one end lies the purely real environment, defined as “whatever might be observed when viewing a real-world scene either directly in person, or through some kind of a window, or via some sort of a (video) display”. At the opposite end lies the purely virtual environment, defined as “environments consisting solely of virtual objects, examples of which would include conventional computer graphic simulations, either monitor-based or immersive.” The Reality-Virtuality Continuum provides a means of conveying the relationship between the real environment, the virtual environment and everything in between. Milgram broadly defines AR as technology that “augments natural feedback to the operator with simulated cues”. Azuma [6] further defines AR as the “middle ground” between the two ends of the reality-virtuality continuum, and defines AR systems as having three characteristics. They must combine virtual and real environments, be interactive in real-time, and register display objects in 3-D.

Milgram additionally splits AR into two distinct technology categories. “See-through” based AR displays allow the user to directly view the real environment through the display, and typically use some form of light reflection or refraction, such as mirrors or waveguides, to superimpose images onto the display area. This provides a maximum sense of presence and the highest degree of “realspace imaging” [5]. Alternatively, monitor based AR displays use cameras to display a real-time video feed of the real environment to the user. Since the image in this case has been digitized, any number of digital effects may be applied to any part of the image,

While both categories meet the broad definition of AR, the differences in technology allow for widely different display techniques and resulting experiences. This thesis effort deals exclusively with “see-through” based AR technology.

2.2 Applicability of Legacy Studies

2.2.1 The Duplo Block Test

Setting aside the technological aspect (older studies were limited by the technology of the time) of the studies found which seek to compare AR-based display methods with various traditional display methods, many studies have largely focused on implementing variations of a “Duplo Block building test” as first designed in 2003 by Tang *et al.* [7]. In the Duplo Block test, subjects must construct a pre-defined assembly using Duplo Blocks of various sizes, shapes and colors. Task instructions as well as various other aspects of the test setup are altered depending on the objective of the specific study. In the 2003 study by Tang *et al.*, subjects were split into four

groups, and each group was assigned a specific display method for a between-subjects comparison. Task performance results for all four methods were compared, with mixed results. The AR active display method demonstrated an improvement in accuracy, but it did not demonstrate a significant improvement in task speed over the corresponding AR passive display. However, this study setup has numerous factors about it that tend to work against the favor of AR based display methods. Blocks are typically either pre-sorted and placed in separate buckets (Blattgerste *et al.* [8]), or unsorted and placed in one bucket [7]. There are only a few total types of blocks (8 total, in study [8]); therefore, there are only a few total bucket locations. This means that it is easy for participants to quickly memorize the starting location of each block. When the participants in these studies use the paper method of instructions, they are more than likely simply memorizing the spatial location of the buckets, such that when they see the instructions for the “blue block”, they instantly know where to reach, possibly without even looking. The subjects are essentially memorizing part of the task.

Because of this, any metrics associated with reaching for a block in a pre-identified location would be less meaningful, and probably should not be used when comparing the effects of information display methods on human performance. By contrast, Robertson [9] presents an updated version of the Duplo Block test setup which accounts for this by removing the act of initially locating the block. Each block placement, or trial, starts with the block already in the subject’s hand. The user clicks a button to start the task, which simply requires them to place the block based on the

instructions they subsequently receive. Robinson's dissertation specifically looked at the effect of registration error, or the error between a display object's perceived location and its intended location in the physical world, on a user's ability to complete a discreet task.

Unfortunately, this Duplo Block test setup is really only analogous to one type of use for an AR HMD; namely, assembling small to medium sized objects from presorted and/or predefined parts on a small centralized workstation. This test setup doesn't immediately lend itself to larger workstations, or to other types of discreet tasks such as plugging in wires, flipping switches, etc.

2.2.2 Individualized / Task-Specific Studies

The collection of studies related to situation-specific AR research is extensive. Numerous industries and disciplines, from manufacturing [8, 10, 11], healthcare [12] and automobile design [13, 14] to Department of Defense applications [15] and space exploration [16, 17, 18], have made strides toward AR-based human performance improvement. However, most of these studies by their nature are situation-specific. Due to this, the designs of these studies, as well as their results, often do not correlate well across disciplines. In other words, the results of an AR-based human performance test designed around assembly line manufacturing (such as [8], [10] and [11]), might not translate to an aircraft mechanic role, due to fundamental differences between the two work environments.

Di Capua [16] conducted a study published in 2009 utilizing the University of Maryland Space Systems Lab (SSL) MX-2 experimental spacesuit analog. In it, test subjects were tasked with completing a simplified pegboard procedure, while receiving instructions via either an AR Static Display or an AR Active Display. The task was completed in the SSL's neutral buoyancy tank, with the subjects inside of the MX-2 suit. The static display in the study was a see-thru LCD that displayed a checklist of steps, while the active display was a SONY Glasstron PLM-S600 HMD system, which displayed active symbology overlying the workstation. The workstation in this study was a series of holes into which pegs were placed, according to a pre-defined procedure. Di Capua concluded that the premise behind the AR Active Display technique was compelling enough to warrant further development and research. However, the current state of the technology made it difficult to adequately compare with a static display due to numerous technological deficiencies including non-stereoscopic display, lack of variable focal distance for symbology, limited angular size of the HMD display, and limited refresh rate of the camera/computer system.

Chintamani [17] conducted a series of studies, published in 2010, pertaining to a human operator's ability to control the end-effector of a robotic manipulator. His research centered on providing AR navigational aids to the user in order to reduce navigation errors, deviations from the optimal end-effector path and total end-effector trajectory distance while completing a simulated on-orbit telerobotic operation. The experimental setup was designed to replicate an "orbital replacement unit exchange",

a task which occurs frequently on the International Space Station and often involves the use of a robotic manipulator, such as the Canadarm2. Interestingly, Chintamani found that the implementation of AR navigational aids reduced reversal errors, or when the user mistakenly moves the end effector closer to the starting location than the ending location, by up to 55%. Overall path distance was also reduced. However, the AR navigational aids did not appear to significantly decrease the overall time to complete the task, a result which was not expected by Chintamani.

Mitra [18], designed and conducted an experiment, published in 2018, as a joint collaboration between Mississippi State University, National Aeronautics and Space Administration (NASA), and Physical Optics Corporation. The goal of this study was to evaluate human integration with various display methods intended for the Mark III spacesuit and eventually the Exploration Extravehicular Mobility Unit (xEMU) spacesuit, which NASA intends to use for future lunar and Mars exploration. In it, test subjects were again tasked with completing a simplified procedure, part of which incorporated a peg placement aspect. The study went through efforts to design a simulated EVA environment, complete with external stressors, in order to more closely approximate the anticipated environment in which the display method will eventually be used. The study compared performance between a non-registered AR display and a traditional EVA cuff checklist. Mitra concluded that the AR display consistently demonstrated promising early results compared with the cuff checklist, however a larger sample size was required to demonstrate statistical significance. In order to achieve this though, the exact setup would need to be recreated, and even

then the results would not necessarily be applicable outside of the narrow discipline window of the study. By narrowing the scope of applicability, the implications of the study results as well as the future usefulness of the test setup are narrowed.

The underlying question with this area of research has not been adequately addressed yet: “Are AR based display methods scientifically proven to be better than legacy methods, from a human performance standpoint?” The way to answer this question would be to design an experiment that attempts to remove all ties to any specific workplace situation, and only employs well defined, discreet tasks which are commonplace among a range of possible AR applications. This ensures that its results would be applicable to as wide an area of research as possible. The 2003 study by Tang *et al.* [7] attempts to do this, however as mentioned above, their methodology was incomplete and flawed, and they were limited by the technology of the time. Few studies were found in the publicly available literature which attempt to do this.

One notable exception is the study by Angelopoulos [19]. In it, subjects were tasked with placing various shaped “erector set” parts in precise locations and orientations relative to a reference shape on a piece of paper. The two independent variables for the study were AR cued instructions and traditional cued (paper) instructions. Position and orientation errors were measured to 1 mm accuracy, and efficiency was calculated for various types of placement tasks. Angelopoulos found that AR was significantly more efficient than paper instructions for every placement task.

2.3 *The Pegboard Study*

The study described herein (specifically Chapter 3: Study Development created a modern, robust “standardized test” which can be applied to many different information display methods and devices. This test setup would be applicable to any situation in which the user is tasked with grabbing an object and moving it. Termed the Pegboard Study and associated “pegboard test”, this setup was used to quantitatively determine the differences between an AR-based static display “checklist” method of information presentation, and an AR-based active display “symbology” method of identifying target objects.

2.3.1 **Test Subject Preparation/Training** through 2.3.3 **Researcher – Induced Bias** highlight a few key areas of the Pegboard Study, and describe how they differ from past studies.

2.3.1 Test Subject Preparation/Training

In studies [7, 8 and 11], the participants were given a practice session prior to the actual task. The participants were allowed to perform the same practice session as many times as they liked until they were “comfortable” and “ready to proceed”, as reported verbally by the participants themselves. There are concerns with this methodology, which are best summed up as follows:

- a) No attempt is made to verify that the participant’s performance metrics with a particular method have reached the bottom of the learning curve, or plateaued, which would indicate that they have progressed past the initial learning phase for that method. Without doing so, the researchers have no way of knowing if the participants are still learning a particular information presentation method, even

as they complete the actual study task. At the very least, this would introduce uncertainty into the data set, which is otherwise unaccounted for and unacknowledged by the authors of both studies.

- b) Even if the authors did attempt to allow participants to plateau (there is no mention of it in either paper), allowing the participants to perform *the same task* over and over again in the process would introduce bias due to memorization of the practice session. The researchers should have presented the participants with different, unique practice tasks each time they opted to repeat the training.

Conversely, test subjects for the Pegboard Study underwent a robust training process to teach them how to use the HMD system as well as each display method, before conducting the official test. 4.3.5 Performance **Scores** describes this process in detail.

2.3.2 Accuracy Measurements

Studies [7, 8, 11, 16 and 18] all defined accuracy as simply the number of mistakes made by the test subject. This is a 1-dimensional measurement, as it doesn't assign a magnitude to a particular mistake or take into account differences between different types of mistakes. The Pegboard Study measures accuracy as a spatial measurement, defined by how accurately the test subject places a peg within the 2-dimensional constraints of the pegboard; for example, how many holes away were they from the target hole? It also takes into account mistakes made by misidentification of the target hole. If the test subject goes for the CORRECT grid location, but on the WRONG

board section, the mistake is counted differently than for spatial accuracy. 4.4.2 Accuracy **Measurement** describes accuracy measurement in detail.

2.3.3 Researcher – Induced Bias

Efforts were taken within the Pegboard Study to remove the effects of researcher-induced bias from test results. Researcher-induced bias can manifest during activities like making a decision to aggregate or not aggregate data, choose a particular data cut-off threshold, or simply choose to reject a data point as an anomaly.

However, arguably a more elusive source of researcher-induced bias, which appears to be often overlooked in the current relevant literature, is in the inherent design of studies. The layout of procedures, the sequence of events to take place, and the mechanisms by which a subject advances through a study can all potentially sway the resulting data in favor of one result or another, potentially without the researchers noticing.

For example, a common mechanism in the literature for advancing subjects through a test appears to be a pseudo voice-controlled advancement mechanism [7, 11], sometimes referred to as a “Wizard of Oz” setup [11]. When the subject completes a step, they might say a key word such as “Next Step”, and a researcher performs the action which triggers the next step, such as clicking a button on the computer. In this situation, it would be easy for the researcher to artificially advance one subject through the task set differently than another subject. Different task advance timing might result if done by different researchers or even by researchers on different days.

Even if a researcher is particularly attentive to preventing this, the risk and uncertainty is still there, and has not been mitigated.

A better practice would be to design the study to be as autonomous as possible, and to limit a researcher's ability to "get in the way" of the task. That said, reasonable trade-offs must always be considered in any study, if one is to produce meaningful results in a timely fashion. A researcher might determine that the cost to implement a fully automated aspect of a study is infeasible. However, they may be able to identify reasonable accommodations which still give the subject greater autonomy over individual aspects of the task at-hand, which helps to limit bias and uncertainty in the results.

In this study, efforts have been made to make the practice and test sessions as "hands-off" as possible for the researchers, in order to limit their ability to influence results (see Chapter 3: **Study Development** and 4). It was determined that certain aspects of the study would be prohibitively difficult to automate, namely when researchers are grading the subject's performance as described in 4.3.5 **Performance Scores**.

Chapter 3: Study Development

A significant portion of this research effort has been the development of a robust standardized test for comparing information display methods, which utilizes a fundamental, discreet task that is ubiquitous across a range of AR applications. The rationale for this decision is that, the more fundamental the test, the more widely applicable are its results. The resulting pegboard test grew out of the concept of a Fitts' Law Tapping Test [20, 21], which has been used since at least as early as the '90s as an indicator of human-computer interaction performance, such as moving a mouse cursor to a desired on-screen location.

3.1 Pegboard

Central to the study is the physical pegboard test apparatus, seen in Figure 2.

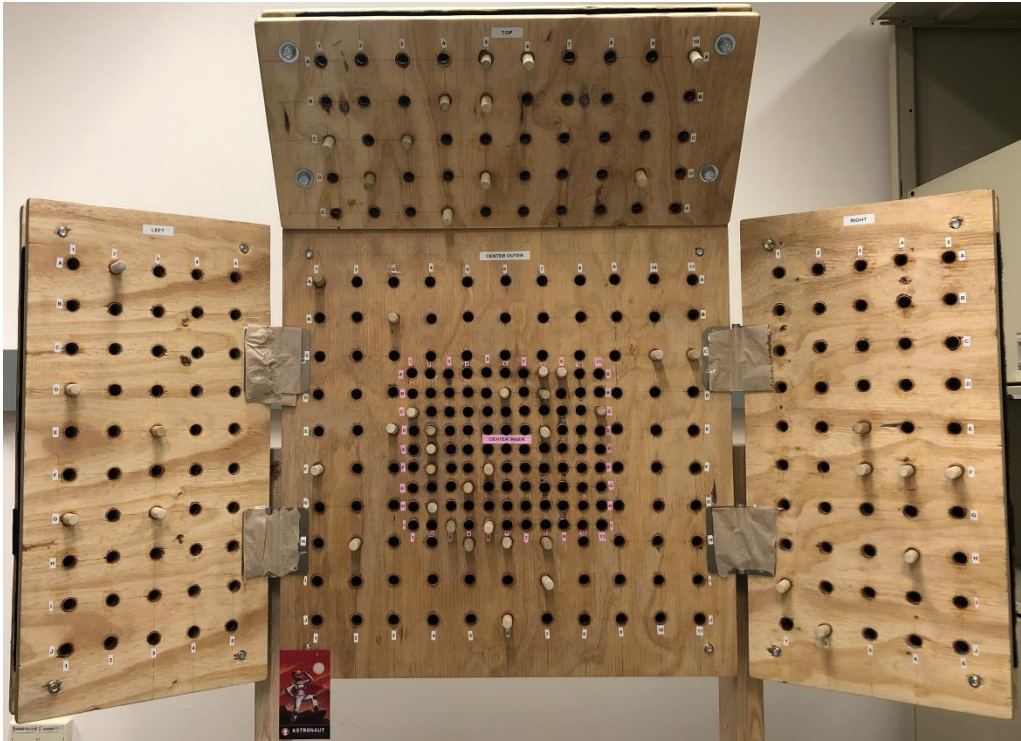


Figure 2: Pegboard Test Apparatus

It is comprised of a center section, with left, right and top wings that are hinged and fold out to the desired angle. The purpose of this configuration was to place every board section at approximately arm's length for an average test subject, while being perpendicular to their line of sight. Hinge angles were set at about 36° for the duration of the study. While this did not perfectly fit most test subjects, changing the hinge angle would have required altering the accompanying CAD model, and creating a separate subroutine for each model in the underlying code, which would have been prohibitively time consuming for the study. It was determined that, since test subjects were free to lean forward and move their upper bodies around during the study, using

an approximated average hinge angle would be adequate for the purposes of this study. Subject placement within the test area is described further in 4.3.2

Calibration.

Each hole in the pegboard is 9/16 inch in diameter and lined with a copper jacket so as to prevent eventual splintering [16] of the holes with repeated use, which could affect test results and could pose a hazard to test subjects and examiners. The copper was smoothed and de-burred to prevent snagging of the wooden pegs on the rim of a hole. Based on the recommendations of [16], an alpha-numeric labeling scheme was employed. Vertical dimensions are labeled with letters, starting at the top of each section. Horizontal dimensions are labeled with numbers, starting at the far left of each section.

3.1.1 Center Section

The center section is 4 square feet in area (24 inches by 24 inches) and contains 189 holes, split between inner and outer subsections. The inner subsection contains 99 holes arranged in a 9x11 (vertical X horizontal) grid, with one inch of spacing between holes. This grid size was chosen as it roughly approximates the size of the display window of the HMD, when viewed from a seated position at an average arm's length. The center section is labeled in a different color (Figure 2) to differentiate those labels from that of the outer section.

The outer subsection contains 90 holes arranged in a 10x11 grid with a two-inch spacing, around the perimeter of the inner subsection.

3.1.2 Left, Right and Top Wings

Each wing is 2x1 square feet (12 by 24 inches) and contains 50 holes arranged in a 10x5 grid, with the top wing rotated 90° in-plane. The holes are spaced two inches apart.

3.1.3 Backing Board and Pegs

Behind each pegboard section is a backing board, which limits the depth that the pegs can be inserted. The backing board depth is adjustable by adding or removing spacers to the attachment bolts. The depth was set at 1.5 inches for this study. The backing board is covered with a layer of loop-sided Velcro, to aid in retaining the pegs after placement.

The pegs were made from ½-inch diameter wooden dowel rods, cut to 2 ½ inches in length. This results in about 1 inch of peg protruding from a hole, which was found through experimentation to be the optimal length for gripping a peg. Each peg is topped with a hook-sided circular Velcro cutout. 50 pegs were used for the large workstation size (Big Board), and 15 pegs were used for the small workstation size (Small Board). The experimental design, including the reasoning behind the layout of the pegboard, is discussed in 4.3 Day-of-Practice **Procedures**.

3.2 Microsoft HoloLens HMD

A Microsoft HoloLens HMD, 1st generation (Figure 3) was chosen for this study due to its availability for use, as well as the existence of an extensive catalogue of online

documentation supporting development [22].



Figure 3: Microsoft HoloLens HMD

The HoloLens HMD has a display FOV of approximately 35° horizontally by 17° vertically.

3.2.1 Noted Differences Between HMDs

Early in the study an interesting factor arose that could affect data collection and should be considered in future studies using AR equipment. During development, a second HoloLens HMD was acquired in order to test repeatability aspects of the study software. It was demonstrated that the same Unity-built study software, called the pegboard program, could be installed on the second HoloLens and executed with minimal effort. However, differences in the functional performance of the pegboard program were noticed between the two HMDs. Differences largely centered on the HMD's ability to keep track of hologram placement in the real environment, while the user moved their head. The problem was exacerbated by the presence of more holograms in the display (display clutter). However, once the user's head stopped moving, both HMDs were able to adequately settle the holograms back to their assigned locations with minimal final distance error.

HMD 1 (Figure 3, pictured above) had a noticeably slow refresh rate, when updating the graphical location of holograms to account for head movement. However, even with this effect, HMD 1 did a reasonable job of keeping holograms in their correct places during head movement. The largest spatial discrepancy observed was less than half an inch. Refresh rate was on the order of 10-15 Hz, depending on display clutter.

HMD 2 (not pictured), conversely had a much smoother refresh rate. However, holograms tended to wander much further from their assigned locations while the user's head was moving, on the order of 4-6 inches. This led to some minor discomfort when the user's head stopped moving, and holograms suddenly snapped back to their assigned locations. This effect persisted, even with minimal display clutter.

Based on these experiences, it was decided that HMD 1 possessed the more comfortable experience and would be used for the duration of the study.

Upon further inspection, it was determined that HMD 1 contains a newer operating system and firmware, even though both HMDs were updated simultaneously. This led the investigators to conclude that HMD 2 might have older hardware which prevents it from updating to the latest software/firmware. Unfortunately hardware version information, such as processor version, is not available through the device user interface, and might not be accessible without physically disassembling the device.

3.2.2 HoloLens Remote Clicker

A Bluetooth connected remote clicker was utilized for this study for navigating through all aspects of the pegboard program (Figure 4).



Figure 4: Microsoft HoloLens “Clicker” Remote Controller

This remote clicker comes with the Microsoft HoloLens and is designed to replace the traditional “airtap” clicking gesture that a user would perform to select something. It was determined that the remote clicker produced less selection errors over time compared to the airtap gesture, since it employs a physical button click to select something. The clicker does not need to be within view of the HMD cameras to work properly, allowing for a more comfortable and reliable experience for the user. Conversely, the airtap gesture requires the hand to be positioned upright and in front of the HMD cameras, and sometimes requires multiple efforts for the gesture to be captured by the gesture recognition software. It was determined that the clicker would provide a more reliable overall experience for the user. Therefore, the pegboard program was designed around this method of item/menu selection.

3.3 Software Development Platforms

3.3.1 Siemens NX 11

The pegboard was modeled using Siemens NX 11. The pegboard CAD model (Figure 5) was created after the physical pegboard was constructed. This was done to ensure that all dimensions of the CAD model, particularly the precise hole locations and hinge angles, match up to the physical pegboard and not to a predefined blueprint, which the physical pegboard may deviate from.

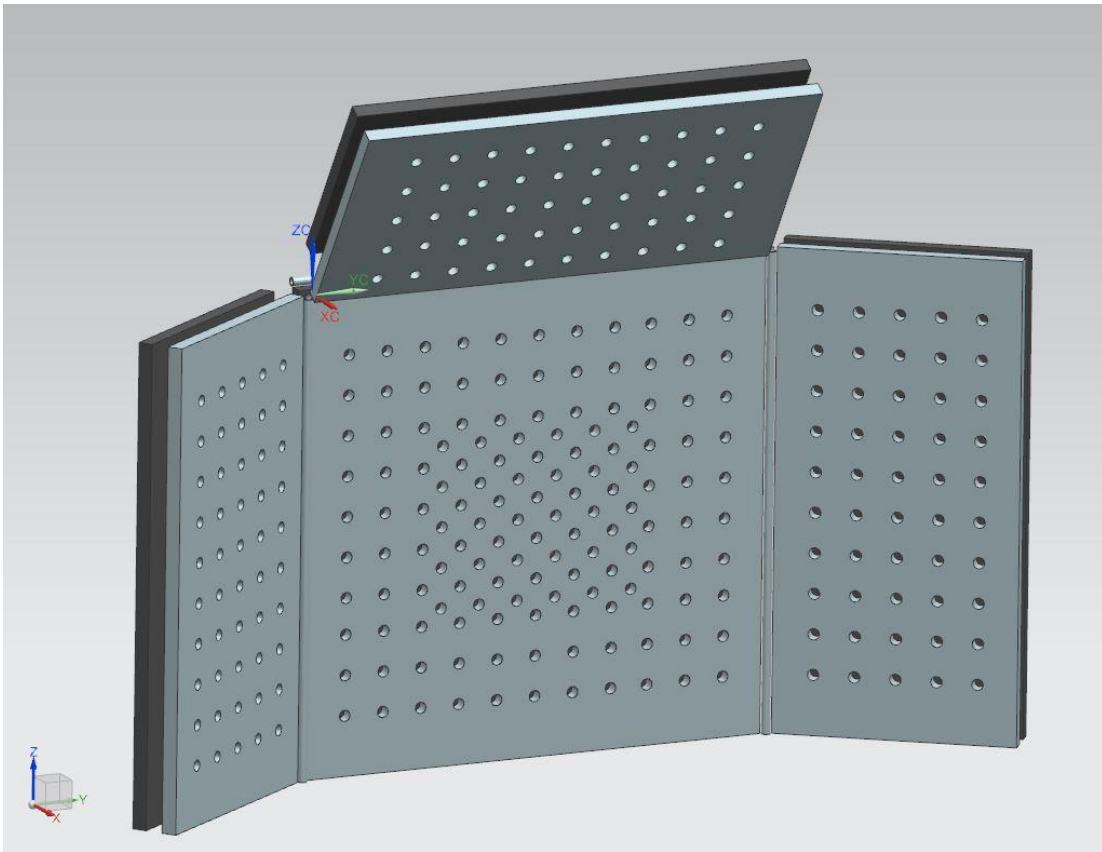


Figure 5: Pegboard CAD Model Assembly

Accurate modeling of the CAD model was essential to ensuring that the subsequent HMD symbology matched up precisely to the physical pegboard apparatus.

3.3.2 MATLAB 2017

MATLAB 2017 was utilized to generate the sequence of randomized peg movements for each portion of the study (see C.1 MATLAB **Random Number Generator**). Each hole on the pegboard was assigned a number from 1 to 339. The MATLAB script generates an initial starting set of 50 random holes, which were used as the starting locations for the 50 pegs. The remaining 289 holes are considered to be the set of empty holes. Then, 10 unique pegs and 10 unique empty holes are randomly selected from their respective sets, without repeating a peg or a hole. This represents the 10 peg movements that constitute Run #1. Each selected peg is paired with the corresponding selected hole, in order of selection. This method prevents a hole or peg from being used twice within the same run, which could introduce compounding accuracy errors (described in 4.3.5 Performance **Scores**). Once the 10 pegs and 10 holes are identified, the sets of filled holes and empty holes are both updated, and the process is repeated. For the official test session, a set of 6 runs were produced for each workstation size. For the practice session, a set of 100 runs were produced for each workstation size, to ensure that a test subject would likely not run out of different practice runs. The variable array output “peg_movements” contains the pegs that get moved in each run (column 1), and the locations they get moved to (column 2). The matrix “all_peg_locations” contains the locations of all 50 pegs at the beginning of each run.

3.3.3 Pegboard Program Development

Unity 2018.2.1f1 was used for this study, along with compatible versions of Vuforia Mixed Reality Tool Kit (MRTK) (2017) and Microsoft Visual Studios (2017). The

combined layout of the Game window (left), Scene Window (center), and C# script (right) are seen in Figure 6.



Figure 6: Software Layout

The process of developing the pegboard program resembled the development of a modern videogame within Unity.

3.3.3.1 Unity

Unity provided the virtual workspace, known as the Unity Scene Editor, in which the individual items within the program, known as assets, were created and physically

arranged (Figure 7).

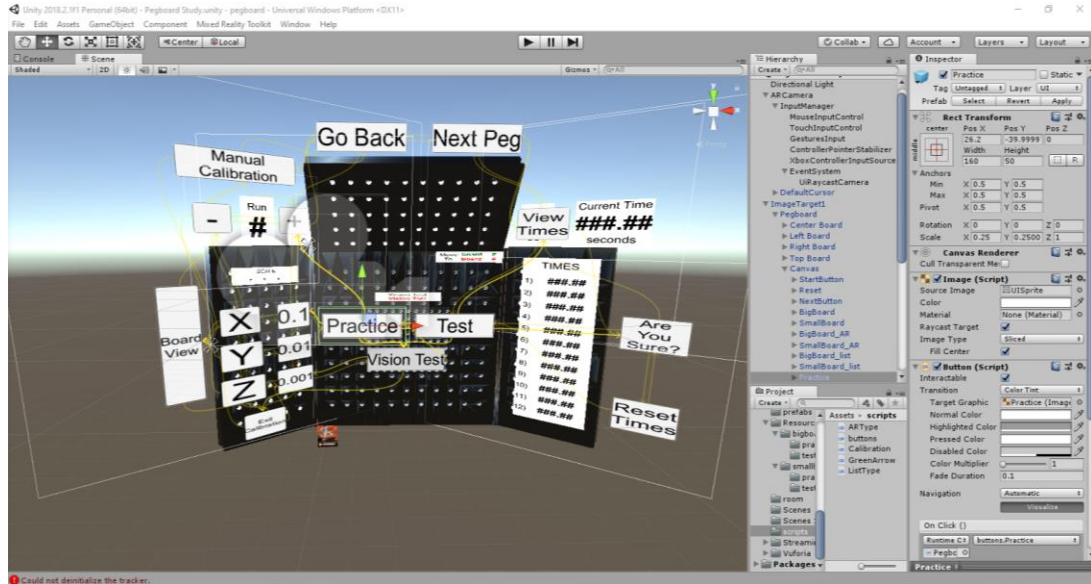


Figure 7: Unity Scene Editor.

The “initial” starting parameters for all assets within the program such as size, color, position, boolean state, etc. are defined here, although the accompanying C# script (3.3.3.2 Microsoft **Visual Studios**) is capable of immediately redefining any of those parameters upon startup. The interrelationships between assets can be viewed graphically here as well, seen as yellow connecting lines and arrows.

The game window shown in Figure 8 depicts an “operational” version of the pegboard program, as it would appear on the headset.

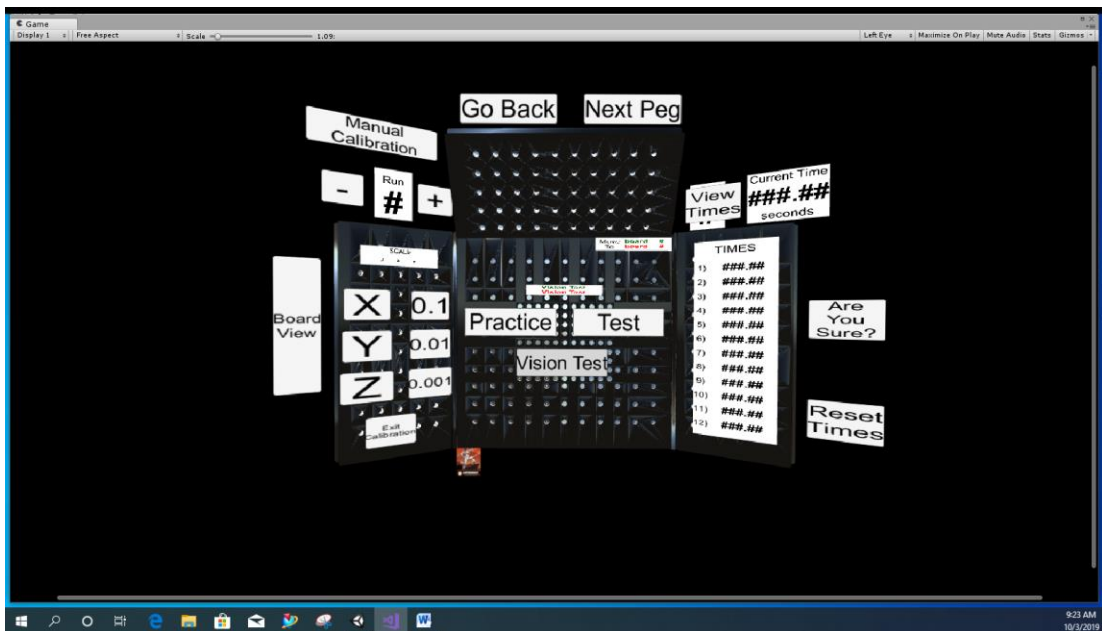


Figure 8: Unity Game Window

All assets are shown simultaneously in Figure 8 for documentation purposes. Some assets, such as the Big Board button, are overlaid by other assets, such as the Practice button.

3.3.3.2 Microsoft Visual Studios

As mentioned above, control of each asset is governed by a C# script, which was created and modified within Microsoft Visual Studios (Figure 9).

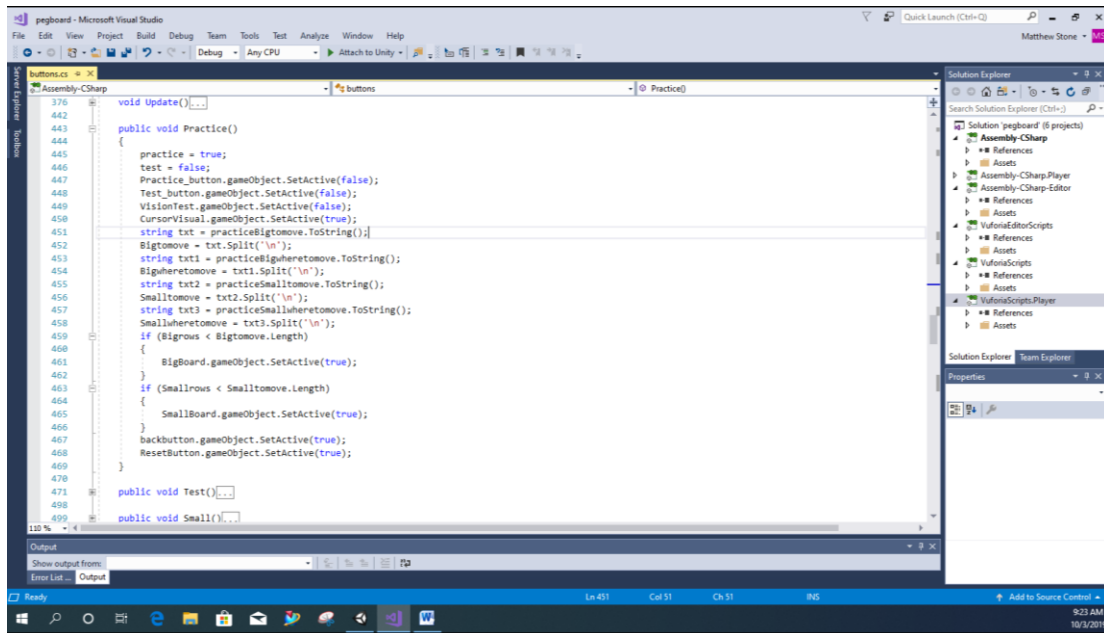


Figure 9: Pegboard Study C# Script Sample

In order to add an object to the pegboard program, it first needed to be created within the Unity scene, and then defined within the C# script. Individual assets within the scene are controllable from here using methods, i.e. “`public void Practice()`”, depicted in Figure 9. Contained within the method are all of the actions that take place when the Method is triggered. This particular method is triggered when the Practice button is clicked, and it causes the Practice, Test, and Vision Test buttons to deactivate, the Big Board and Small Board buttons to activate, and some boolean values to change.

3.3.3.3 Vuforia MRTK

The Vuforia MRTK add-on (upper tab seen within Figure 7) contains a selection of pre-build assets and C# scripts which are capable of recognizing predefined image targets and placing holograms accordingly. By placing the virtual image target at a known location within the Unity scene and printing out the real version of the target to-scale, the Unity scene can be placed at a location in the real environment based on the location of the printed image target. In order for this to work, the HMD cameras must be able to see and recognize the printed image target in the real environment. For comparison, notice the placement of the red image target on the lower-left corner of the pegboard in Figure 7 and Figure 2.

Once the image target is acquired, the scene is placed accordingly. As long as the image target stays within view, the HMD will continuously update the location of the scene based upon its perceived location of the image target. This means that if the image target is moved during this time, the scene will move with it.

If the image target is subsequently lost (which happened frequently), the HMD immediately freezes the location of the scene in the real environment, based on its built-in spatial mapping feature. If the user moves their head during this time, the Scene will remain in place in the real environment, barring deviations mentioned in 3.2.1 Noted **Differences Between HMDs**. Once the image target is reacquired, the HMD automatically resumes placement of the scene relative to the target.

Chapter 4: Study Procedures

This chapter describes the design, methodology and rationale for the Pegboard Study, as well as the procedures followed for all volunteer human test subjects. As stated in Chapter 2, the rationale behind developing a “standardized” test was to address known methodology issues with past experimental designs, while creating a test from which the results would be as widely applicable as possible. Therefore, great effort was taken to design the study in such a way so as to remove or reduce potential effects of bias due to differences between individual subjects, order of procedure, the specific choice of HMD, and so on. Again, the goal of this study was to investigate and quantify the differences between an AR “active” display and an AR “passive” display on human performance.

Before diving into aspects of the study, it is prudent to define some relevant terms.

4.1 Study Definitions

- Pegboard – the physical test apparatus as described in 3.1 Pegboard.
- Test conditions – there are 4 distinct test conditions that were analyzed as part of this study: Big Board Holograms, Big Board Checklist, Small Board Holograms, and Small Board Checklist.
- Visual display method – there are two distinct visual display methods which were analyzed as part of this study: Holograms (the “active” display) and Checklist (the “passive” display). Each display method presents one peg movement at a time to the test subject.

- Big Board – refers to the large workstation size, utilizing the entire 3x4 square foot pegboard.
- Small Board – refers to the small workstation size, utilizing only the central portion of the center board, as described in 3.1.1 Center **Section**.
- Holograms – refers to the display method of providing active symbology within the HMD FOV, which directs the test subject’s attention to objects of interest. For the Small Board Holograms test condition, colored ring holograms were centered around pegs of interest to draw the test subject’s attention to them. For the Big Board Holograms test condition, colored rings were again used when the target of interest was within the HMD FOV. When the target was not within the HMD FOV, colored targeting arrow holograms were used to direct the test subject’s attention toward the target object. These arrows ride on a circle around the edge of the HMD’s FOV, and point in the direction of the target object. When the object (and the colored ring) falls within the FOV of the HMD, the arrows disappear, leaving behind the colored ring to mark the target location.
- Checklist – or simply List Method; refers to the display method of providing a hologram checklist, which is “pinned” to the pegboard, and displays one peg movement at a time. The Checklist utilizes the alpha-numeric grid layout described in 3.1 Pegboard to call attention to specific pegs and holes.
- Peg movement – or simply a movement; the act of taking one peg from a hole location on the pegboard, and placing it in another hole location.
- Run – a set of 10 peg movements in succession.

- Series – All of the runs which comprise a similar test condition, for one test subject. During the official test, this was 3 runs per test condition, for every test subject. For the practice session, this was unique to every test subject (described in 4.3.5 Performance **Scores**).
- Session – Comprised of 4 series, one for each test condition. Each test subject completed a practice session and a test session.
- Study – The compilation of all practice and test sessions for all test subjects, and the resulting data analysis.

4.2 Study Logistics

The Pegboard Study was conducted in room 2A56, Bldg. 2187 (Engineering South) at Naval Air Station (NAS) Patuxent River, in Southern Maryland. Visual and auditory distractions were minimized to reduce influence on test results. The study was approved by the Naval Air Warfare Center Aircraft Division (NAWCAD) Investigative Review Board (IRB), in order to ensure safety of the test subjects and conformance with government accepted guidelines for human subject testing (see Appendix D: **IRB Protocol** for the IRB protocol). Test subjects were recruited from the general workforce on base and were compensated for their time at their regular salary rate. A total of 24 subjects between the ages of 21 and 57 were tested. Additional subject demographics can be seen in B.1 Test **Subject Demographics**. Once a potential subject was identified, they were scheduled for an initial screening and practice session (day 1), with the official test session taking place the next day (day 2). Subjects were considered to be official test subjects for data collection

purposes once they completed and passed the Vision Test. However, all subjects were reasonably compensated for their time.

4.3 Day-of-Practice Procedures

4.3.1 Human Subject Forms

When a potential subject came in for day 1, they were first presented with an Informed Consent Document (ICD) and Privacy Act Statement (A.1 **Informed Consent Document and Privacy Act Statement**, which explained details of the study and their rights as a volunteer human test subject. Once they signed the ICD, subjects were given a Health History Questionnaire (HHQ) (A.2 Health **History Questionnaire**).

4.3.2 Calibration

Once the HHQ was complete, subjects were seated at the test station (Figure 10).



Figure 10: Pegboard Study Test Station

The test station was arranged to maximize definable geometries for the HoloLens to detect. Cabinet doors were utilized for this purpose. It was determined that dark areas and reflective surfaces tended to be harder to detect, so white towels were added to provide a textured surface where needed. The smooth metal hinges of the pegboard were covered with coarse brown paper for the same reason.

Subjects were instructed on how to don and doff the Microsoft HoloLens, and how to adjust its position for comfort and maximum display visibility. Subjects donned the

HoloLens, and were instructed on the use of the clicker and how to navigate through menus. The HoloLens brightness was set to 70% and could not be adjusted by subjects, in order to ensure the same brightness level for all subjects. Subjects then completed the HoloLens Calibration Procedure, which digitally adjusts the interpupillary distance of the display and calibrates the various onboard sensors.

Subjects were then instructed to sit upright and back in the chair, and position the chair such that their outreached palms could reach the upper corners of the pegboard (Figure 11, at left).

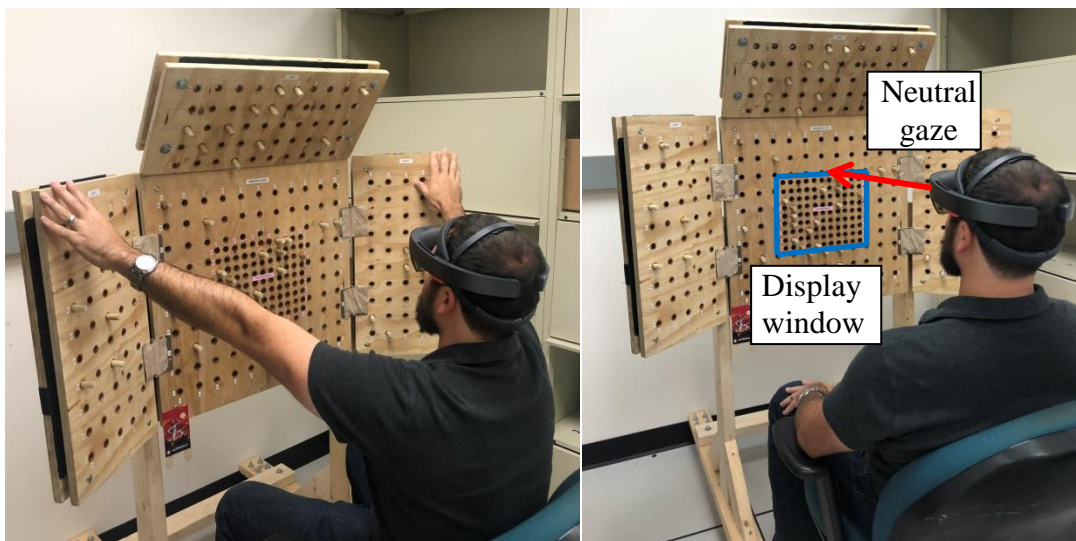


Figure 11: Test Subject Position

MIL-STD-1472G [23] recommends that a viewable workstation, such as a computer monitor, be placed such that the viewer's eyes are level with the top of the screen, and information is presented within about 15° below the horizontal line-of-sight.

Extrapolating from this, it was determined that the central portion of the center board is the most used area of the pegboard and as such, should be positioned as

recommended. The chair was raised or lowered as needed, to position the subject's eye level even with the top row of the inner grid portion of the center board (Figure 11, at right), to account for this. The subject's gaze here is depicted in red. As described in 3.1.1 **Center Section**, at this distance the display window of the HoloLens approximately matches the size of the inner grid portion of the center board, depicted in blue. Once positioned, subjects were instructed to remember that chair/body position for future placement.

Subjects were then instructed to open the Pegboard Study program. Once initialized, subjects were instructed to lean in towards the red image target in the lower-left corner of the pegboard, in order to obtain image target identification. Once the image target was identified, placement of the scene was automatically adjusted (3.3.3 for more detail). Clicking on the Board View button (Figure 7, left side) Figure 7: Unity Scene Editor.would turn on or off the hologram alignment board (Figure 12, left is on, right is off), allowing subjects to visually verify that the scene had been properly aligned.

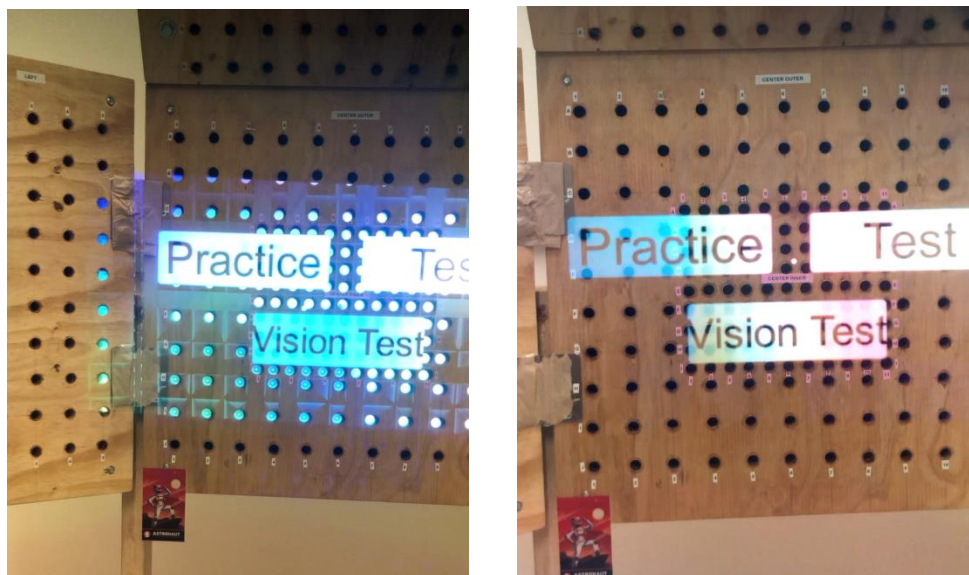


Figure 12: Pegboard Program Alignment Board

Subjects were instructed to repeat this process of image target identification until the holes in the hologram alignment board overlapped with the real pegboard holes by at least half of a hole diameter. It was determined that half of a hole diameter of overlap was sufficient to significantly reduce any ambiguity in Hologram symbology instructions (4.3.4.2 Holograms **Display Method** for more detail). After alignment was complete, the alignment board was turned off.

All buttons and text panels in the study were white, although they do not appear completely white in images due to the method by which the HoloLens generates white coloring. White light is created from the uniform combination of red, green, and blue light projections, in each display. However, when viewing a white hologram, it was observed that each HoloLens display depicts white light with varying intensities of each constituent color, which varies with the local display location. In other words, when viewing a white hologram in one display, some areas of the display appear slightly red, green, or blue. When the opposite display is viewed, the areas of discrepancy are complementary. Therefore, when the two displays are combined by using both eyes simultaneously, the resulting color is much closer to pure white. However, when taking point-of-view images through the HoloLens, only one display can be viewed at a time, resulting in the appearance of off-white coloring as seen in Figure 12.

4.3.3 Vision Test

Once calibration of the test station was complete, subjects were instructed to click on the Vision Test button (Figure 12). The vision test consists of 12 pairs of 8-digit numbers, one above the other (Figure 13).



Figure 13: Vision Test Display

One is always red, and one is always green. However, the locations of the two colors were randomized for each pair. The size and style of the numbers represented the smallest text that a subject would be required to read during the study (the checklist instructions), in the relevant colors.

Subjects were instructed to cover one eye with a provided hand-held eye cover. For each number pair, subjects were instructed to read either the red numbers or the green numbers. Subjects covered their left eye for pairs 1-6, and their right eye for pairs 7-12. 12 total pairs were required in order to reduce the chances of a subject getting through based on guessing alone. If a subject were to guess, they would have a 50%

chance of guessing the right number sequence, for each red/green pair. For 12 total pairs, this reduces to 0.024% for one subject. For 24 total subjects, there is a 0.5% chance that someone could have guessed their way through the entire vision test. This was determined to be adequate (less than 1%) for the purposes of this study. For the case of an individual being color blind in only one eye and needing to make 6 guesses, they would have a 1.5% chance of guessing their way through. A subject who successfully completed the Vision Test was deemed a qualified Test Subject for this study. The reasoning for this is that, if a subject exhibited vision issues such as degraded visual clarity, color blindness, or a lack of stereovision, their performance might skew the results towards a particular variable. Therefore, individuals who did not pass the vision test were excluded from the study (A.1 **Informed Consent Document and Privacy Act Statement** and A.2 **Health History Questionnaire** for more detail).

4.3.4 Practice Session

Every subject was assigned a unique order of test conditions for the duration of the study. Since there were 4 test conditions, there were 24 total permutations of sequences in which they could be completed. In order to reduce the various effects of learning bias, or a subject's propensity to prefer the first test condition they are assigned, all 24 permutations needed to be tested, leading to 24 required test subjects.

Upon completing the vision test, the Unity Scene automatically returns the subject to the main menu (Figure 12). Subjects were instructed to select "Practice", then to

navigate through to their first test condition (Figure 14), and ensure that “Run 1” was displayed above the left board (Figure 14D).



Figure 14: A) Big/Small Board selection (far left), B) Holograms/Checklist selection (middle left), C) Start button (middle right), D) Run counter (far right)

Plus and minus buttons allow for the selection of different runs, should the need arise. Subjects were then instructed on the interpretation and use of their upcoming display format for completing their peg movement task. They were also instructed to place a higher importance on accuracy, and a secondary importance on speed. The final step for each subject, prior to starting a run, was to turn on the “Boardview”, and verify that the hologram alignment was still within the $\frac{1}{2}$ hole diameter limit. If it was not, subjects were instructed to follow the same image target realignment procedure to correct it.

Subjects were then given a verbal countdown to start the run, after which they would complete the run by following the given procedures. When the start button was selected, an on-board timer was initiated which tracked subjects' completion times. The subjects were instructed, via one of two display formats, to move the appropriate peg to the appropriate hole (Figure 15).



Figure 15: Checklist display format (left), and Hologram display format (right)

For both display methods, “green-to-red” methodology was emphasized, meaning that the subject was instructed to take the “green” peg and place it in the “red” hole. Regardless of the display format, subjects completed a set of 10 peg movements, at which point the program stopped the timer, logged the time to a timecard accessible from the menu screen, and increased the run counter. Subjects were instructed not to view their times until they had completed 4 runs for that test condition, so as to reduce any self-competitive biases.

4.3.4.1 Checklist Display Method

The Checklist display method (Figure 15, left) depicted virtual written information on a virtual “piece of paper”, pinned to the pegboard. The checklist was located in the

top right corner of the central board for both Big Board and Small Board test conditions and did not change locations for the study. The top row was green and displayed the target peg, while the bottom row is red and displays the target hole. The Checklist display method utilized a 3-part identifier, as follows: Section-Row-Column. The entire pegboard was divided into five sections: Left, Right, Top, Inner, and Outer. The section/grid identifiers were labeled directly on the pegboard. Therefore, in order to successfully move a peg subjects had to first read the checklist identifier, process the information, then translate that to a board location.

4.3.4.2 Holograms Display Method

The Holograms display method depicted information entirely with symbology (Figure 15, right), which directed the subject to the pegs and holes of interest. The target peg was surrounded by a green circle, whose inner diameter was 50% larger than the physical hole diameter. The target hole was surrounded by a red circle. The hole diameter was selected to account for potential inaccuracy in the hologram alignment. Through development, it was found that when the identifying symbology obscures a user's view of the target peg or hole, this has a detrimental effect on the user's ability to precisely locate that target with their hand, resulting in a longer time to correctly take or place a peg. It was determined that a ring-shaped symbology with an oversized inner hole diameter would be sufficiently reliable in order to prevent an inaccurate hologram alignment from causing this phenomenon. 50% oversizing corresponds with the 50% hole overlap procedure in 4.3.2 Calibration. The outer radius was set equal to the distance between two holes on the inner section.

For the Big Board test condition, subjects were also given a set of guiding arrows to direct their attention toward the target rings. These arrows always remain in front of a user's vision; however, they are "placed" just above the surface of the pegboard so that they appear at the same distance away from the user as the target rings. During development, it was found that when the arrows were set at a constant distance away from the user, they could induce double-vision effects when their perceived depth didn't perfectly match up with the target rings. Additionally, if either the rings or arrows appeared to fall "behind" the surface of the board (i.e. if the hologram alignment shifted slightly, even by as little as half an inch), this could create a different but equally unsettling effect as the user again struggles to reconcile two different focal points. Therefore, all symbology was offset in front of the surface of the pegboard by one inch, to ensure a buffer region in case hologram registration began to drift. Minute registration drift was frequently observed throughout the course of a run, but was well within both the oversizing and offset buffer regions.

4.3.5 Performance Scores

While a subject was completing a run, two researchers used paper scorecards to track the subject's peg movements, in order to catch any mistakes the subject made. If a mistake was made, the location of the mistake was noted on the scorecard next to the correct step (Table 1).

Table 1: Sample Scorecard

Run 1				
Move #	Target Peg		Target Hole	
1	Right-I1		Inner-H8	
2	Top-C3		Outer-I2	
3	Left-D1		Outer-J8	
4	Outer-C10		Outer-E11	
5	Top-A5		Right-J1	
6	Left-A2		Inner-E6	
7	Top-A10		Outer-H9	
8	Outer-E3		Inner-H5	
9	Inner-I3		Left-J1	
10	Top-C1		Outer-C8	
			Run Error:	
			Run Time:	

As mentioned in 3.3.2 MATLAB 2017, the sequence of peg movements was designed so that a mistake in peg selection or placement does not propagate within the same run, except in the unlikely event that the mistake involves an upcoming peg or hole in the sequence (i.e. the subject mistakenly placed a peg in a hole involved in an upcoming step, or conversely took a peg from an upcoming step). It was determined that this particular kind of mistake would be prohibitively difficult to design for in the study, and instead the researchers would note the mistake and allow it to propagate through the run, should it occur. Any mistakes that were made during a run needed to be manually corrected before the start of the next run so that the pegboard was properly set up again.

After a subject completed 4 initial runs for a test condition, they were asked to view and read their times to the researchers. Their times were logged in a spreadsheet such as the example seen in Table 2.

Table 2: Sample Completion Time Scoresheet

Big Board Holograms					
Run #	threshold	Completion Time	delta 1	delta 2	pass/fail
1		102.36			N/A
2		67.81			N/A
3	15.354	61.94	-34.55	-40.42	FAIL
4	10.1715	48.98	-5.87	-18.83	FAIL
5	9.291	44.52	-12.96	-17.42	FAIL
6	7.347	41.28	-4.46	-7.7	FAIL
7	6.678	45.91	-3.24	1.39	PASS
8	0		0	0	
9	0		0	0	
10	0		0	0	

Subjects then completed individual runs until their completion times plateaued.

Plateau is defined as a sequence of three runs (in order) in which the completion times for the SECOND and THIRD runs fall within 15% of the FIRST run.

Completion times in Table 2 above are tracked in the yellow “Completion Time” column. The delta between the 1st and 2nd times is logged in the “delta 1” column.

The delta between the 1st and 3rd times is logged in the “delta 2” column. The “threshold” column denotes the maximum allowable delta value for that given run.

At a glance, in order for the subject to “pass” the run, the magnitude of both deltas must be less than the magnitude of the threshold.

The goal of imposing this plateau criterion onto subjects was to train all subjects to within 15% of their “idealized pace”, thereby reducing the effects of a subject continuing to “learn the system” during their official test runs. Alternatively, forcing all subjects to simply complete the same number of practice runs doesn’t necessarily train everyone to the same level, because some subjects will naturally take more or fewer runs to achieve their idealized pace than others. However, it is generally very difficult for a subject to perfectly and consistently reach their idealized pace as fatigue sets in, and performance generally starts to degrade again after reaching an initial plateau point. From development trials, a 15% threshold was chosen as being close enough to a perfect plateau without being overly difficult to achieve and causing fatigue.

Subjects completed a particular test condition when they achieved “PASS” criteria. Subjects were allowed to take breaks as needed between runs and were encouraged to take breaks between test conditions. The practice session was considered complete when all four test conditions were completed with “PASS” criteria.

4.4 Day-of-Test Procedures

The official test session took place on the day following the practice session, and followed many of the same procedures as the practice session (see 4.3 Day-of-Practice **Procedures**), with a few exceptions. There was no paperwork to complete prior to donning the HoloLens. For each subject, the official test session started with the same HoloLens calibration sequence as in the practice session. Once the HoloLens was calibrated, subjects were instructed to open the pegboard program, and

align with the image target again. Once aligned, subjects were instructed to select “Test”, and to navigate to their first test condition.

4.4.1 Test Sequencing

Subjects completed each test condition in the same order as they did during the practice session. However, the sequence of individual peg movements was changed from practice. As described in 3.3.2 MATLAB 2017, each subject completed 3 runs of 10 movements for each test condition. For each workstation size, every subject completed the exact same runs in the same order, regardless of which display method they used. This eliminated the possibility of one subject getting a faster sequence by chance, or of one particular display format similarly getting faster sequences by chance, which would otherwise introduce error and uncertainty into the data.

4.4.2 Accuracy Measurement

One additional difference from the practice session was the tracking of accuracy errors. Peg accuracy is measured as the number of holes away from the target hole that a test subject misses by, when attempting to take or place a peg. Peg accuracy is measured horizontally and vertically, but not diagonally. For example:

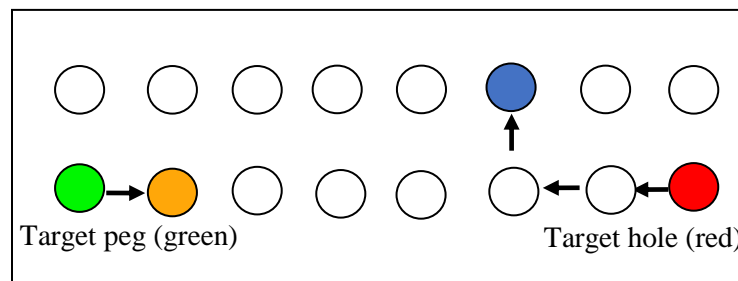


Figure 16: Sample Target Peg (far left) and Target Hole (far right)

In Figure 16 above, the subject is supposed to take the target peg from one hole (shown in green); however, they mistakenly take a peg from another hole (shown in orange) (+1). Similarly, they are supposed to place the peg in the red hole; however they mistakenly place it in the blue hole (+3). The arrows indicate how much the test subject missed by, for both the green hole and the red hole. Counting the arrows yields their total accuracy score for that particular move. In this case, their accuracy score would be $1 + 3 = 4$, for that particular peg movement. A lower score indicates more accurate peg movement. A score of zero would indicate they moved the correct peg to the correct hole. Separately, misidentifying the board section simply counted as +1. Accuracy scores for each movement were summed to yield a total accuracy score for each run.

Once all 3 runs were completed for a particular test condition, the subject was instructed to view and read their times to the researchers. Times and accuracy scores were logged for each run.

4.4.3 Post Test Survey

Once all four test conditions were completed, the subject was instructed to take off the HoloLens and complete a questionnaire (A.3 Post **Study Questionnaire**). The questionnaire was intended to gather a qualitative assessment from each subject on their preference for each test condition, with an approximate magnitude.

Chapter 5: Data Analysis and Discussion

Time and accuracy scores for the official test session were collected for all test subjects, and compiled into the data matrices in B.2 Raw **Performance Data**. For each set of three runs, time scores were averaged while accuracy scores were summed. Any data which was affected by system errors, such as the program freezing/lagging or skipping pegs, was removed from analyses. These data points are indicated in dark red in B.2 Raw **Performance Data**.

5.1 Completion Time

5.1.1 Raw Completion Times

Completion time proved to be the more indicative measure of overall performance for the study, due to the small total number of accuracy mistakes made (see 5.2 Accuracy).

Every subject's average completion times for each test condition were compiled into Figure 17 (see also B.3 Performance Graphs).

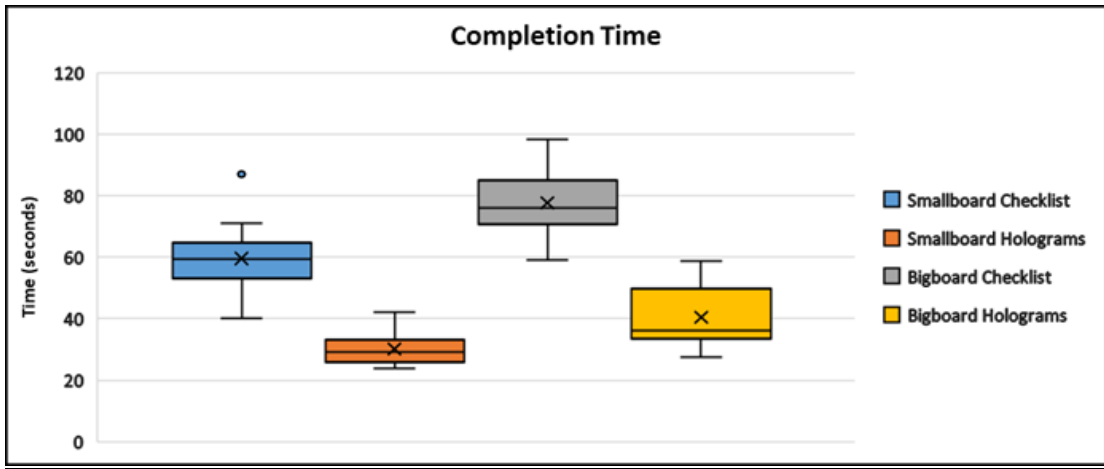


Figure 17: Completion Time Box-and-Whisker Plot

The 1st quartile is denoted by the lower box limit, the median, or 2nd quartile, is denoted by the middle line, the 3rd quartile is denoted by the upper box limit, the mean is denoted by the “X”, and the single lowest and highest values are denoted by the whiskers. The interquartile range (IQR) is represented by the shaded area of the box. One outlier appears in the Small Board Checklist data set, defined as a data point which is at least 1.5 times the magnitude of the IQR either above the 3rd quartile or below the 1st quartile. This outlier has a magnitude of 87.0 seconds and comes from Subject #16.

5.1.2 Comparison of Display Methods

Every subject tended to have their own ideal pace at which they completed their tasks, which is to be expected. However, this works to reduce the significance of individual completion times, as some subjects tended to be naturally faster or slower, regardless of the display method. Of greater significance is the ratio of speeds

between display methods. For each workstation size, dividing the Hologram completion times by the Checklist completion times and taking the inverse (or simply dividing Checklist by Holograms) yields the Holograms-to-Checklist speed ratio (Figure 18).

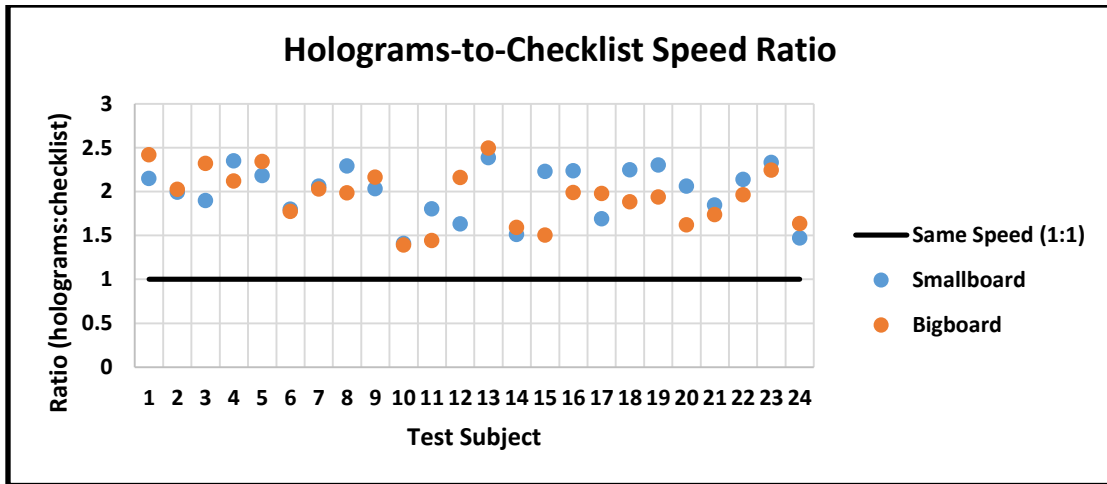


Figure 18: Hologram-to-Checklist Speed Comparison

In Figure 18, the Y-axis denotes the ratio of Hologram completion speed to Checklist completion speed. Values greater than 1 indicate that Holograms are faster. As observed, every subject experienced a faster Holograms speed than Checklist speed, for each workstation size. This was supported by near unanimous qualitative assessments by subjects (Appendix A:). All but one subject preferred the Holograms display method to the checklist display method, for both workstation sizes.

At this point it may be prudent to review the definition of the P-Value, which is used extensively in the following statistical analyses [24]. In statistics, the P-value is

generally defined as the probability that, assuming the Null Hypothesis is true, a random sample will be found which is at least as large (or small) as the current sample. A P-value close to zero indicates that one would be unlikely to find the current sample if the Null Hypothesis were true, indicating that it is highly unlikely that the Null Hypothesis is correct, in which case the Null Hypothesis is rejected in favor of the Alternative Hypothesis. Conversely, a P-value close to 1 indicates that the current sample is likely to have been found under the Null Hypothesis, indicating that the Null Hypothesis cannot be confidently rejected.

Additionally, for the following T-Tests and 2-way ANOVA analysis, one of the underlying assumptions is that the data is representative of a normal distribution of the actual population. Since subject #16 produced an outlier in a dataset (Figure 17, extraneous dot), and to maintain symmetric datasets across the independent variables, the data points associated with subject #16 were not included in the subsequent significance tests.

One-sided Matched Pair T-Tests for each workstation size yield:

Table 3: Matched-Pair T-Tests for each Workstation Size

Null Hypotheses: Hologram Method is no faster than Checklist Method, for both Small Board and Big Board, which would result in a mean difference in completion times of zero.		
	Small Board	Big Board
Observed Mean Difference (seconds)	28.41	35.97
Hypothesized Mean Difference	0	0
Standard Deviation	7.34	9.14
Sample Size	23.00	23.00
Calculated Z-Value (Z_{calc})	18.56	18.87

P-Value (prob. of finding a Z value $\geq Z_{calc}$)	3.114E-19	2.798E-17
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where the matched pair in each test is the two display methods (Holograms and Checklist). Since the P-Value is near zero for each test, the null hypotheses can be rejected with near-certainty.

By changing the Hypothesized Mean Difference in the table above and iterating by hand, Z-Values can quickly be found which correspond to a Significance Level α of 0.01.

Table 4: Hypothesized Mean Difference Corresponding to Significance Level $\alpha = 0.01$

Null Hypotheses		
Small Board: Hologram Method is no more than 24.85 seconds faster than Checklist Method		
Big Board: Hologram Method is no more than 31.53 seconds faster than Checklist Method		
	Small Board	Big Board
Observed Mean Difference (seconds)	28.41	35.97
Hypothesized Mean Difference	24.85	31.53
Standard Deviation	7.34	9.14
Sample Size	23	23
Z-Value (Z_{calc})	2.33	2.33
P-Value (prob. of finding a Z value $\geq Z_{calc}$)	0.01	0.01

With 99% certainty, the null hypotheses can be rejected in favor of the alternative hypotheses: Specifically, that Hologram Method is at least 24.9 seconds faster than Checklist Method for Small Board and 31.5 seconds faster for Big Board.

This supports qualitative observations, experiences and industry marketing claims regarding this technology over the last few years, particularly with the Microsoft HoloLens.

5.1.3 Comparison of Workstation Sizes

It is interesting to note the uniformity by which Hologram Method is faster than Checklist Method for both workstation sizes, across a range of subject demographics recorded in B.1 Test Subject Demographics.

On average, subjects saw an approximately 100% (2x) improvement with Hologram Method over Checklist Method, for both workstation sizes (Figure 19).

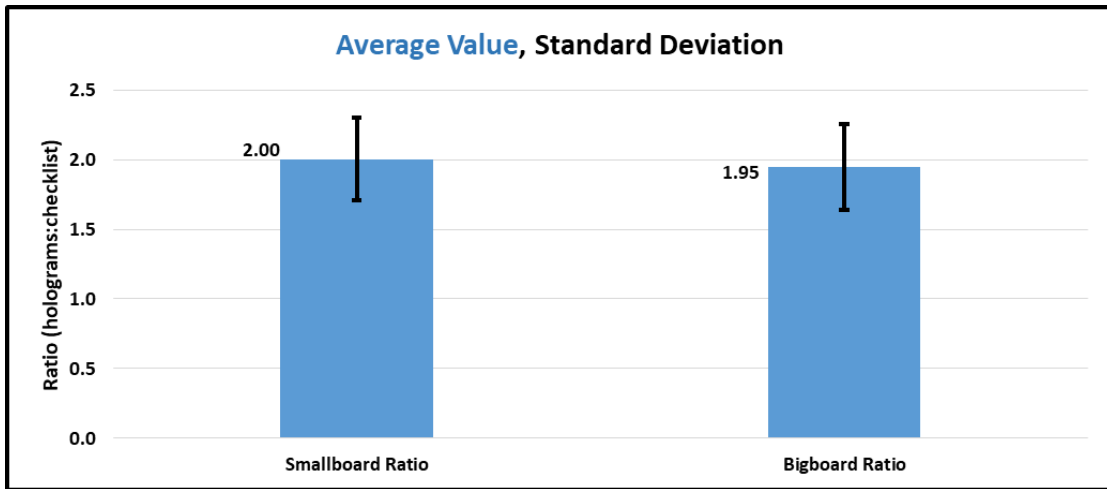


Figure 19: Holograms-to-Checklist Speed Ratio (Holograms:Checklist)

Performing a two-sided Matched Pair T-Test, with the two workstation sizes as the matched pair and the speed ratio as the analyzed metric yields:

Table 5: Matched Pair T-Test for Speed Ratios across Workstation Sizes

<p>Null Hypothesis: There is no significant difference in speed ratios between workstation sizes. This would result in a hypothesized DELTA between the two</p>

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workstation speed ratios of 0.	
Observed Mean Speed Ratio Delta	0.046
Hypothesized Mean Speed Ratio Delta	0
Standard Deviation	0.299
Sample Size	23
Z-Value (Z_{calc})	0.733
P-Value (prob. of finding a Z value $\geq +Z_{calc}$ or $\leq -Z_{calc}$)	0.618

As is observed in Table 5, the calculated P-Value corresponding to the null hypothesis is well above the $\alpha = 0.01$ Significance Level. Therefore, one cannot reject the Null Hypothesis based on the current dataset. Importantly however, this does not indicate that one can automatically accept the null hypothesis; rather, that the current dataset does not significantly disprove it. This will be revisited in 5.1.4 2-Way **Analysis of Variance.**

A comparison of performance metrics vs. demographics can be seen in B.3 Performance **Graphs**. Reorganizing the data in Figure 18 by age and time of day (Figure 21 and Figure 22 in Appendix B.3) did not immediately reveal any significant trend lines. Similarly, filtering the data by demographics (Figure 23 through Figure 27 in Appendix B.3) did not reveal any notable changes to the calculated mean speed ratio, with one possible exception. Male subjects experienced a 105% increase in Holograms speed over Checklist speed for both workstation sizes, while female subjects experienced an 88% increase for Small Board and a 69% increase for Big Board (Figure 24 in Appendix B.3).

The same two-sided Matched Pair T-Test analysis as described above was performed again, for both the male and female subsets:

Table 6: Matched Pair T-Test for Speed Ratios across Workstation Sizes, for both Male and Female Test

Subjects

Null Hypotheses:		
There is no significant difference in speed ratios between workstation sizes, for both Male and Female test subjects. This would result in a hypothesized DELTA between the two workstation speed ratios of 0, for both Male and Female datasets		
	Female	Male
Observed Mean Speed Ratio Delta	0.196	-0.020
Hypothesized Mean Speed Ratio Delta	0	0
Standard Deviation	0.288	0.288
Sample Size	7	16
Calculated Z-Value (Z_{calc})	1.801	-0.279
P-Value (prob. of finding a Z value $\geq +Z_{calc}$ or $\leq -Z_{calc}$)	0.281	0.833

Even though the female subject population demonstrated differing average speed ratios across the two workstation sizes, the resulting P-Values (Table 6) are much larger than 0.01, suggesting that the Null Hypotheses again cannot be rejected, for both gender subsets. In other words, even though the difference in speed ratios varied between the male and female subject populations, the differences are not statistically significant enough to reject either of the Null Hypotheses.

5.1.4 2-Way Analysis of Variance

A 2-Way Analysis of Variance (ANOVA) analysis is generally used to determine if there is any inter-relationship between two independent variables in a data set, in other words, if changing one independent variable affects the other independent variable's effect on the dependent variable [25]. Here an ANOVA analysis was conducted to investigate the inter-relationship between workstation size and display

method. These independent variables were considered as the two factors in the analysis. Each factor has two possible states, or levels, resulting in a 2X2 ANOVA analysis. Again, completion time was considered as the dependent variable for the analysis. Excel 2016 with the Data Analysis add-on was used for this analysis, specifically the “Anova: Two-Factor With Replication” tool. As in the above analyses, a 1% or 0.01 Significance Level α was considered.

Table 7: Completion Time ANOVA Results

ANOVA	3 Null Hypotheses: There is no relationship between any of the 3 sources of variation, at left, and the dependent variable.					
<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Workstation Size	4444.131	1	4444.131	69.55584	9.34E-13	6.931941
Display Method	23485.33	1	23485.33	367.5728	3.59E-33	6.931941
Interaction	371.0798	1	371.0798	5.807831	0.018037	6.931941
Within	5622.584	88	63.893			
Total	33923.12	91				

From Table 7, the P-values for each independent variable are near-zero. This suggests that we can reject the first two null hypotheses in favor of the alternative, specifically that there is a strong correlation between each independent variable and the resulting completion time value. This agrees with earlier analyses in 5.1.2 **Comparison of Display Methods**. Changing either the workstation size or the display method significantly changes the time to complete the task.

The 3rd P-value indicates whether or not there is a significant interaction between the two independent variables: In other words, whether changing the value of one variable alters the other variable's effect on the results. Since the 3rd P-value in Table 7 is 0.018, the Null Hypothesis cannot be rejected with 99% certainty, or at the 0.01 Significance Level. It can, however, be rejected with 98.2% certainty (1 – 0.018). This suggests that it can be said with 98.2% certainty that changing one variable changes the other variable's effect on the results. Importantly for this analysis, it indicates that changing the workstation size does, in fact, result in a change to the speed ratio (the effect of changing the display method) as discussed in 5.1.3 **Comparison of Workstation Sizes**, and which Table 5 was unable to prove.

It is very important to note, however, that the ANOVA analysis does not make claims towards any other behavior regarding the interaction, including the magnitude. It is only an indication of whether the correlation exists or not. This is to say that, while the interaction may be significant from a statistical standpoint, it is not necessarily meaningful from a scientific standpoint. Additionally, the ANOVA analysis only demonstrated correlation, not causation. Therefore, an accurate statement of the results would be:

With near 100% certainty, subjects experienced a speed increase of 100% for the small workstation and 95% for the large workstation on average, when switching

from Checklist to Holograms display method. Additionally, with 98.2% certainty, changing the workstation size correlates with the change in speed ratios.

From this statement, one can then debate the scientific meaningfulness of a 5% change in speed ratio, which would likely be dependent on the contextual background of the debate. However, one could enter the debate with a high degree of confidence in the numerical values.

5.2 Accuracy

As mentioned in 4.3.4 **Practice Session**, subjects were instructed to place primary importance on accuracy, and secondary importance on speed when completing the runs. Perhaps consequently, only eight total accuracy errors were made throughout the study, by six subjects. These errors are indicated in orange in B.2 **Raw Performance Data**.

All accuracy errors in the official test occurred during the Checklist Display Method. In other words, the Hologram Display Method produced no accuracy errors. Due to this, it is impossible to calculate the extent to which Holograms were more accurate than Checklist. Some basic demographic comparisons can be made, however. Two mistakes were made on the Small Board, and six were made on the Big Board. Five male subjects and one female subject made accuracy errors. Five of those subjects were during the morning, while one was during the afternoon. To the question of whether or not they had prior Augmented/Virtual Reality experience, five of those

subjects responded with “no prior experience”, and the sixth subject responded with “Once”. The six subjects fell across a range of ages.

5.2.1 Matched Pair T-Test

A One-Sided Matched Pair T-Test can still be conducted to determine the significance of the results.

Table 8: Matched-Pair T-Tests for each Workstation Size

Null Hypotheses: Hologram Method is no more accurate than Checklist Method, for both Small Board and Big Board, which would result in a mean difference in accuracy scores of zero.		
	Small Board	Big Board
Observed Mean Difference (seconds)	0.09	0.26
Hypothesized Mean Difference	0.00	0.00
Standard Deviation	0.29	0.69
Sample Size	23.00	23.00
Calculated Z-Value (Z_{calc})	1.45	1.82
P-Value (prob. of finding a Z value $\geq Z_{calc}$)	0.077	0.038

The P-Values in Table 8 indicate that the results are not significant enough to reject the Null Hypotheses with 99% confidence. Therefore, even though every accuracy mistake occurred with the Checklist Display Method, there simply weren’t enough total mistakes made to confidently say that Hologram Method is more accurate than Checklist Method.

5.2.2 2-Way Analysis of Variance

As previously, a 2-Way ANOVA analysis was performed on the data to determine if any significant inter-relationship exists between the independent variables, this time considering accuracy scores as the dependent variable.

Table 9: Accuracy ANOVA Results

ANOVA		3 Null Hypotheses: There is no relationship between any of the 3 sources of variation, at left, and the dependent variable.				
<i>Source of</i>						
<i>Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F</i>	<i>P-value</i>	<i>F crit</i>
Workstation Size	0.173913	1	0.173913	1.248227	0.266932	6.931941
Display Method	0.695652	1	0.695652	4.992908	0.027985	6.931941
Interaction	0.173913	1	0.173913	1.248227	0.266932	6.931941
Within	12.26087	88	0.139328			
Total	13.30435	91				

Once again, the lack of total data points prevents any of the three Null Hypotheses from being rejected with 99% confidence, though the display method comes close. With 97.2% confidence, the Null Hypothesis can be rejected in favor of the alternative, specifically that there is a relationship between Display Method and accuracy.

5.3 Qualitative Measurements and Observations

As described in 4.4.3 Post **Test Survey**, subjects filled out post-study questionnaires (A.3 Post **Study Questionnaire**) after completing the test session. All subjects reported that they preferred the hologram display method to checklist display method, for both workstation sizes, with one exception. One subject preferred the checklist method for the small board workstation and cited the frequency with which the target circle appeared outside of the HMD FOV and the lack of directional arrows as the cause for their preference.

Several other subjects also cited the same issue, namely, that when the target circle appeared along the edge of the smaller workstation, it was possible for the target to be off-screen. This, combined with the lack of directional arrows, would leave the subject with no way of knowing which way to look, resulting in an “edge-scanning” motion until they located the target. This effect appeared to be more prevalent for subjects of smaller stature, who tended to sit closer to the workstation. Their display FOV would have covered a smaller area of the workstation, resulting in occasional loss of symbology during the small board holograms test condition. While subject anthropometrics were taken into account for positioning purposes, specific anthropometrics including arm length were not recorded for this study. Future work may involve investigating the effects of providing continuous on-screen symbology compared to intermittent symbology.

Beyond this, subjects also reported that the holograms display method reduced the mental workload of the task, by transferring the task of interpreting the instructions to the headset. This resulted in less mental fatigue and longer endurance over time, especially with the large workstation. This effect was also noticed qualitatively by the researchers during practice sessions. Interestingly, subjects generally reported on their questionnaires that they preferred the Big Board holograms method over the Small Board holograms, even though averaged questionnaire metrics suggest a slight preference for the reverse. All subjects preferred the addition of the guiding arrows over not having them, and many cited this specifically in the questionnaires as the reason for their abovementioned preference for Big Board Holograms.

5.3.1 Matched Pair T-Test

As in previous sections, a one-sided Matched Pair T-Test analysis was completed to determine the significance of the post study questionnaire metrics, found in B.4 Questionnaire **Metrics**.

Table 10: Matched Pair T-Tests for each Workstation Size

Null Hypotheses: Hologram Method scores no better than Checklist Method, for both Small Board and Big Board, which would result in a mean difference in scores of zero.		
	Small Board	Big Board
Observed Mean Difference (metric score)	1.21	2.00
Hypothesized Mean Difference	0	0
Standard Deviation	0.93	1.14
Sample Size	24	24
Calculated Z-Value (Z_{calc})	6.35	8.58
P-Value (prob. of finding a Z value $\geq Z_{calc}$)	3.12E-06	3.41E-09

From Table 10, P-values near zero indicate that there is a significant difference in user ratings between display methods, for each workstation size. Adjusting the hypothesized mean difference and iterating yields:

Table 11: Hypothesized Mean Difference Corresponding to Significance Level $\alpha = 0.01$

Null Hypotheses: Hologram Method scores no more than 0.77 higher than Checklist Method for Small Board, and 1.46 higher for Big Board		
	Small Board	Big Board
Observed Mean Difference (metric score)	1.21	2.00
Hypothesized Mean Difference	0.77	1.46
Standard Deviation	0.93	1.14
Sample Size	24	24
Calculated Z-Value (Z_{calc})	2.33	2.33
P-Value (prob. of finding a Z value $\geq Z_{calc}$)	0.01	0.01

With 99% confidence, the holograms display method ranks at least 0.77 higher than checklist display method for the small workstation, and 1.46 higher for the large workstation.

Chapter 6: Conclusion

6.1 Summary and Recommendations

The effect of implementing an active symbology augmented reality display into a user's work environment is to increase the user's task completion speed by approximately 100%, for the given task and workspace environment of the study. This holds true for two different workstation sizes, approximately 35° and approximately 90° at arm's length, resulting in a 100% and 95% speed increase, respectively. This also holds true for various subject demographics including age, time of day in which the test was conducted, whether or not the subject uses corrective lenses, and prior augmented/virtual reality experience. A slight disparity in improvement was observed between genders, however it is theorized that this is due to anthropometric differences between subjects, and not specifically due to gender. Female subjects tended to be slightly smaller in stature on average, however specific anthropometrics for this study were not recorded for either gender, preventing this hypothesis from being investigated further using the current data set.

No accuracy mistakes were made during the holograms display method, making this display method appear at first glance to be more accurate than checklist display method. However, the low number of total mistakes made throughout the study results in a low statistical significance for this result. For future testing, external stressors such as a time constraint could be applied in order to produce more accuracy

mistakes, which may yield a more statistically significant accuracy difference between display methods.

Subjects reported qualitatively and through ratings that they greatly preferred the active symbology over the static checklist symbology. Interestingly, many subjects reported qualitatively that they preferred the additional guiding arrows even more than just the illuminated target rings alone, citing a further decrease in perceived cognitive workload. However, averaged ratings indicate that the Big Board holograms test condition, which utilizes the arrows, was very slightly more difficult than the Small Board holograms test condition. This could be due to the larger workstation size, which tends to make all tasks performed on it more difficult or longer to complete compared with the smaller workstation, due to larger average movement distances.

It is recommended that the pegboard test and associated procedures be considered as a candidate for use as a “standardized test”, for future research related to AR-based information display methods. It has demonstrated its efficacy in providing direct comparisons between display methods, as well as its reliability and ease of use.

Additionally, it is recommended that future test protocols utilizing the pegboard test also capture individual peg movement times, either through instrumentation or video capture. This will allow for the measurement and analysis of the index of difficulty, a traditional Fitts’ Law metric [20].

6.2 Future Applications

Given the demonstrated magnitude and consistency of improvement in task speed, these results appear to justify the implementation of AR-based active display symbology into an array of workplace environments. Furthermore, the quantitative analysis provides a starting point for determining a possible return on investment associated with specific applications. Knowing the cost of a typical HMD, the rough time-savings it would yield, the value of that time for a given task, and the total time required to complete the task (assuming the task has a definable end), one could determine if implementing the HMD for the specific task would save or cost money over the course of the task. This would go a long way towards determining if implementation for a specific task is worth it.

In terms of task relevance, the smaller workstation size is representative of tasks which might involve identifying specific bolts or areas, wiring a panel, or flipping switches on a control board. Any number of tasks might fall into this category, from a non-destructive inspection of a metal component, to identification of parts on an assembly line, to training a pilot on cockpit switch operations. An astronaut servicing a satellite might be required to access a panel and remove bolts in order to replace a battery.

The larger workstation represents the same types of tasks, but in an environment where the task at hand is not directly in front of the user. For example, a mechanic might have to frequently look away from the local workstation to find a tool, then

return to the workstation to finish the task. Giving them the ability to quickly relocate the region or item they were working on would certainly save time. In the astronaut example, this might be more indicative of near-future operations in more remote locations, such as on the lunar surface. In the future, an astronaut might find themselves having to repair equipment on the surface of the moon during an EVA, in much the same way a mechanic or maintainer repairs equipment on earth. They might have to turn away from the workstation or leave it entirely to locate a tool, before continuing on with their repair task. Artificial task guidance in this case could enable them to complete their task faster, thereby lowering the overall risk associated with the EVA.

6.3 Continuation of Research

Based on the results of this study, a follow-on study is currently underway at NAS Patuxent River to investigate and compare the effects of additional display methods on a user's task completion time and accuracy. A "floating" checklist which stays fixed to the lower portion of the display window, as well as a physical hand-held paper checklist, are being compared to the display methods discussed in this study. All other aspects of the study are being kept the same. This will help to construct a more complete picture of performance improvement for a user, as they transition from a paper checklist, to a floating checklist, to a virtual "pinned" checklist, and finally to a full active-symbology display, all else being held constant.

A logical next step after this follow-on study would be to investigate the effects of external stressors, such as a perceived time constraint, distractions, degraded

environment, and poor visibility among others. Robertson's [9] research answered many questions regarding the effects of AR registration error on human performance, though this may be worth revisiting with the pegboard test, as well. These next steps would help to determine how the performance improvement behavior of AR changes depending on external conditions.

6.4 Final Thoughts

The "business as usual" model taken thus far by many in the AR research community has been to focus on very specific applications for each study. While this serves the needs of the application at hand, this does not serve the needs of the larger community. Continuing to take this approach will almost surely guarantee that the full scope of possibilities, benefits, and hindrances of AR is never fully realized. Alternatively, by taking the holistic research approach outlined here, the performance benefits of AR in many different types of applications may be determined much more quickly. Going forward, this may be the best strategy to bring the science up-to-pace with the technology.

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Appendix A: Test Subject Documentation

A.1 Informed Consent Document and Privacy Act Statement

Naval Air Warfare Center Aircraft Division (NAWCAD) Informed Consent And Privacy Act Statement

Protocol/Research Title: Effects of Augmented Reality Based Object Illumination on Human Performance and Task Completion Time (Short Title: AR Based Object Illumination)

Protocol #: NAWCAD.2019.0002-IR-EP4

Principal Investigator: Matthew Stone

Phone:

Fax:

Email Address:

Code:

Bldg/Room:

1. I am being asked to voluntarily participate in a Minimal Risk research study entitled: Effects of Augmented Reality Based Object Illumination on Human Performance and Task Completion Time
2. The purpose of this study is to determine whether Augmented Reality (AR) based illumination of real objects could aid a user in completing a predetermined set of tasks with greater speed and/or accuracy.
3. The study will last for 3 months.
4. On the preliminary visit, I will be briefed by either the Principal Investigator (PI) or the Associate Investigator (AI) on the purpose and procedures for this research study.

I understand the research will require the following: The ability to see in binocular vision, without any form of blindness or color blindness, vision in both eyes commensurate with the ability to drive a vehicle (corrective lenses are allowed), a vision screening (to be conducted at the beginning of the session), and 2.5 hours of total time commitment, split between two sessions of 1.5 hours and 1 hour.

5. There will be approximately 24 subjects enrolled in this study.
6. I understand that the investigators believe that the risks or discomforts to me are as follows: This study will employ the use of a Microsoft HoloLens head mounted display (HMD). The Microsoft HoloLens HMD, and AR in general,

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presents several known risks to user comfort. These can include temporary feelings of nausea, motion sickness, dizziness, disorientation, headache, fatigue, eye strain, or dry eyes, and may be more prevalent for first-time users.

Additionally:

- I understand that if I have a history of seizures, I will be unable to participate as this study will require me to use a head mounted video display system
 - I understand that I must be at least 18 years old to participate in this study.
7. I understand that there are risks to my comfort, if I am or should become pregnant; while the Microsoft HoloLens and Augmented Reality are not known to present any additional safety risks to a pregnant individual or the unborn fetus, pregnancy can increase the risk for experiencing nausea and motion sickness related symptoms while using the Microsoft HoloLens.
 8. The benefits I may expect from my participation in this study are minimal. I understand that I will receive no direct benefit other than the knowledge that participation in this study will aid efforts to improve the performance, safety and/or effectiveness of the United States Navy. I may have a copy of any publications resulting from the current study, if I so desire.
 9. I understand that a chargeable object is available if required, in order to compensate for my time participating in this study.
 10. I should incur no out-of-pocket expenses due to my participation in this protocol.
 11. I understand that if I think that I have a research-related injury, I will notify the Principal Investigator immediately at NAWCAD.2019.0002-IR-EP4.

I understand if I am injured because of my participation in this research and I am a DoD healthcare beneficiary (e.g., active duty military, dependent of active duty military, retiree), I am authorized space-available medical care for my injury within the DoD healthcare system, as long as I remain a DoD healthcare beneficiary. This care includes, but is not limited to, free medical care at DoD hospitals or DoD clinics.

I understand if I am injured because of my participation in this research and I am not a DoD healthcare beneficiary (e.g., civil service), I am authorized space-available medical care for my injury at a DoD hospital or a DoD clinic. Medical care charges for care at a DoD hospital or a DoD clinic will be waived for my research-related injury. If I obtain care for research-related injuries outside of a DoD hospital or clinic, I will not be reimbursed for those medical expenses.

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For DoD healthcare beneficiaries and non-DoD healthcare beneficiaries, except for emergent injuries sustained during active participation in the research trials, I understand transportation to and from hospitals or clinics will not be provided, or paid for, by the DoD. Unless I am covered by TRICARE, no DoD reimbursement is available if I incur medical expenses to treat research-related injuries. No compensation is available for research-related injuries.

I understand that this is not a waiver or release of my legal rights.

12. If I have questions about this study I should contact the following individuals: For questions about research (science) aspects, contact: Matthew Stone at (###) ###-#### or (###) ###-####. For questions about medical aspects, injury, or any health or safety concerns I have about my participation, contact: CAPT William Padgett at (###) ###-####. For questions about the ethical aspects of this study, my rights as a volunteer or any problem related to protection of research volunteers, contact: Mr. Stephen Coleman, the Chair of the Institutional Review Board (IRB) at (###) ###-####. For questions about my subject rights or related issues, contact: the Human Subjects Advocate, HMC Craig Denbleyker at (###) ###-####.

13. My confidentiality during the study will be ensured by assigning me a coded identification number. My name will not be directly associated with any data. The confidentiality of the information related to my participation in this research will be ensured by maintaining records only coded by identification numbers. Research studies occasionally are evaluated by the IRB and other oversight agencies (i.e., Department of Navy (DoN) Human Research Protection Program or Office of Naval Research) to determine that the study was conducted properly. If such an evaluation is requested for this study they may have a need to inspect my research record. These records may include my military medical record in order to complete their evaluation. Information about subjects will remain confidential to the greatest extent possible.

14. My participation in this study is completely voluntary. If I do not want to participate there will be no penalty and I will not lose any benefit to which I am otherwise entitled. I may terminate my participation in this study at any time. If I choose to terminate my participation, there will be no penalty or loss of any benefit to which I am otherwise entitled.

15. For research involving military personnel, Unit Officers and Non-Commissioned Officers (NCOs) shall not influence the decisions of their subordinates to participate, or not to participate as research subjects. Unit Officers and Senior NCOs in the chain of command shall not be present at the time of research subject solicitation and consent during any research recruitment sessions in which members of units under their command are afforded the opportunity to participate as research subjects. When applicable, officers and NCOs so excluded shall be afforded the opportunity to participate as research

subjects in a separate recruitment session. During recruitment briefings to a unit where a percentage of the unit is being recruited to participate as a group, an ombudsman not connected in any way with the proposed research or the unit shall be present to monitor that the voluntary nature of the individual participants is adequately stressed and that the information provided about the research is adequate and accurate.” (DoDD 3216.02 section 4.4.4.)

16. If I decide to withdraw from further participation in this study, there will be no penalties. To ensure my safe and orderly withdrawal from the study, I will inform the PI, Matthew Stone at (###) ###-#### or (###) ###-####. Matthew Stone would like me to understand that I may discontinue my participation in this study at any time I choose without penalty.

17. My participation in this study may be stopped by the PI at any time without my consent if the PI believes the decision to be in my best interest. Although unlikely, possible reasons that would make this necessary include: previously undisclosed medical circumstances, or symptoms thereof, which would disqualify me from participation (for example, exhibiting symptoms of a previously undisclosed propensity towards photosensitive epileptic seizures, which may have been previously unknown to myself). There will be no penalty or loss of benefits to which I am otherwise entitled if my participation is stopped.

18. Any significant new findings developed during the course of the research which may relate to my willingness to continue participation will be provided to me.

19. I have received a statement informing me about the provisions of the Privacy Act.

20. I have been given an opportunity to ask questions about this study and its related procedures and risks as well as any of the other information contained in this consent form. All of my questions have been answered to my satisfaction. I understand what has been explained in this consent form about my participation in this study. At this time I do not need any further information to make a decision whether or not to volunteer as a participant in this study. If at any time, I do have any questions after the research study has begun, I am free to ask the PI or the NAWCAD IRB at any time. I voluntarily give consent to participate. I will be given a copy of this form for my records.

Volunteer Signature	Print Name	Date
---------------------	------------	------

Investigator Signature	Print Name	Date
------------------------	------------	------

PRIVACY ACT STATEMENT

1. Authority. 5 U.S.C. 301
2. Purpose. Human Factors/Human Performance information will be collected in an effort to determine whether augmented reality based virtual object illumination affects a user's ability to complete a predefined set of tasks, in a study titled "***Effects of Augmented Reality Based Object Illumination on Human Performance and Task Completion Time (Short Title: AR Based Object Illumination)***," Protocol NAWCAD.2019.0002-IR-EP4, which will assess whether virtual illumination of real objects increases a user's speed and/or precision in completing predefined tasks.
3. Routine Uses. Human Factors/Human Performance information will be used for analysis and reports by the Departments of the Navy and Defense and other U.S. Government agencies. Use of the information may be granted to non-Government agencies or individuals by the Navy Surgeon General following the provisions of the Freedom of Information Act or contracts and agreements. I voluntarily agree to its disclosure to the agencies or individuals identified above and I have been informed that failure to agree to this disclosure may make the information less useful. The "Blanket Routine Uses" that appear at the beginning of the DoN's compilation of medical databases also apply to this system.
4. Voluntary Disclosure. Provision of information is voluntary. Failure to provide the requested information may result in failure to be accepted as a research volunteer in an experiment or removal from the program.

A.2 Health History Questionnaire

VISUAL HEALTH HISTORY SCREEN

Research Subject ID #: _____

1. Sex (Circle One): Female Male
2. Age: _____
3. Have you ever been diagnosed with or experienced any of the following conditions: (check below)
 - ___ Blindness in one or both eyes
 - ___ Red/green color blindness (the inability to distinguish between reds and greens)
 - ___ Blue color blindness (the inability to distinguish blues and yellows, which may appear as white/gray)
 - ___ Achromatopsia (the inability to distinguish between all colors)
 - ___ Photophobia (extreme sensitivity to light)
 - ___ Photosensitive epileptic seizures
4. Do you have the ability to pass the Maryland State Driver's License **Vision Test**? (binocular vision, visual acuity of 20/40 in each eye w/corrective lenses, and continuous field of vision of at least 140 degrees)
Yes No
5. Do you wear corrective lenses daily?
Yes No
6. Do you have any history of blurry vision or lapse of vision?
Yes No
7. Are you easily susceptible to motion sickness or disorientation?
Yes No
8. Do you have any prior experience using a virtual reality or augmented reality head mounted display? (for ex. Microsoft HoloLens, Oculus Rift, etc.)
Yes No

If yes, with which system, and what is your approximate experience level (only once, monthly, daily)?

9. Have you ever experienced severe motion sickness and/or disorientation as a result of the use of a virtual reality or augmented reality HMD?

Yes No

If so, how long did it last, and how was it mitigated, if at all?

10. **Female Subjects:** Are you, or could you possibly be, pregnant at this time?

Yes No

If yes, please be aware some people may experience temporary nausea and motion sickness symptoms while experiencing augmented reality, and pregnancy may increase your likelihood of experiencing these symptoms.

11. Are you currently taking any medications (prescription and/or over the counter or herbal supplements)?

Yes No

If so, what?

Additional Comments:

A.3 Post Study Questionnaire

POST STUDY QUESTIONNAIRE

Research Subject ID #: _____

1. On a scale of 1 (difficult) to 5 (easy), please rate each test set

Small pegboard, checklist	1	2	3	4	5
Small pegboard, holograms	1	2	3	4	5
Large pegboard, checklist	1	2	3	4	5
Large pegboard, holograms	1	2	3	4	5

2. For the small pegboard, which was your preferred display method and why?

3. For the large pegboard, which was your preferred display method and why?

Appendix B: Raw Data

B.1 Test Subject Demographics

Table 12: Test Subject Demographics

Test Subjects	Male/ Female	Age	Time of Day	Corrective Lenses	Prior VR/AR Exp
1	M	28	700	no	No
2	M	25	900	no	Once
3	M	28	1300	yes	every 2 months
4	F	27	1120	no	No
5	M	32	800	no	twice
6	F	27	1300	no	weekly
7	M	21	1000	no	No
8	M	34	800	no	daily
9	M	28	1435	yes	No
10	F	28	730	no	No
11	F	23	730	no	No
12	M	50	1100	yes	Yes, frequency?
13	M	22	655	yes	No
14	M	40	1000	yes	~5 times, daily use in the late 90's
15	F	25	1300	no	No
16	M	57	1030	yes	No
17	M	41	800	no	No
18	M	29	1300	yes	No
19	M	30	1300	no	~5 times
20	M	24	930	yes	Once
21	M	22	755	no	No
22	F	28	1000	no	Quarterly
23	M	33	1215	no	No
24	F	32	1400	yes	Once

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B.2 Raw Performance Data

Table 13: Test Subject Raw Data – Checklist Method

Display Method	Checklist															
Workstation Size	Small Board								Big Board							
Test Metric	Time (seconds)				Accuracy				Time (seconds)				Accuracy			
Test Subject #	Run #1	Run #2	Run #3	mean	Run #1	Run #2	Run #3	sum	Run #1	Run #2	Run #3	mean	Run #1	Run #2	Run #3	sum
1	60.2	48.2	51.0	53.1	0	0	0	0	88.8	83.2	79.9	84.0	0	1	0	1
2	49.1	48.7	44.7	47.5	0	0	0	0	69.6	67.5	60.4	65.8	0	0	0	0
3	55.2	53.9	53.1	54.1	0	0	0	0	78.7	71.4	74.1	74.7	0	0	0	0
4	69.6	58.5	63.7	64.0	0	0	0	0	90.5	73.8	67.5	77.2	1	0	0	1
5	57.9	59.3	61.2	59.5	0	0	0	0	86.1	79.6	79.7	81.8	0	0	0	0
6	47.7	45.2	47.9	46.9	0	0	0	0	67.7	61.8	61.7	63.7	0	0	0	0
7	62.5	69.4	58.3	63.4	0	0	0	0	73.2	78.1	69.8	73.7	0	0	0	0
8	73.4	62.3	64.2	66.6	0	0	0	0	70.9	72.0	76.3	72.0	0	0	0	0
9	63.5	59.7	55.6	59.6	0	0	0	0	76.7	69.5	71.6	72.6	0	0	0	0
10	58.8	52.1	48.6	53.2	0	0	0	0	78.5	72.0	72.5	74.3	3	0	0	3
11	56.5	53.5	50.4	53.5	0	0	0	0	70.2	70.3	63.4	66.8	0	0	0	0
12	40.8	37.9	41.4	40.0	0	0	0	0	60.1	62.7	54.9	59.2	0	0	0	0
13	61.3	54.8	53.9	56.7	0	0	0	0	86.7	82.2	77.5	82.1	0	0	0	0
14	66.6	63.4	60.7	63.6	0	0	0	0	105.5	79.8	82.2	89.1	0	0	0	0
15	70.2	73.3	69.6	71.0	0	0	0	0	87.9	91.7	85.3	88.3	0	0	0	0
16	87.5	92.2	81.1	87.0	0	0	0	0	101.5	98.1	95.4	98.3	0	0	0	0
17	64.3	61.8	58.5	61.5	0	0	0	0	87.2	73.8	72.8	77.9	0	0	0	0
18	72.5	72.2	67.6	70.8	1	0	0	1	106.0	89.1	92.8	96.0	0	0	0	0
19	63.1	61.7	59.0	61.3	0	0	0	0	89.8	79.0	70.0	79.6	0	0	0	0
20	54.9	54.2	49.8	53.0	0	0	0	0	84.0	64.5	65.3	64.9	1	0	0	1
21	58.8	55.6	56.5	57.0	0	1	0	1	73.8	62.8	60.2	65.6	0	0	0	0
22	57.8	55.7	52.1	55.2	0	0	0	0	83.5	65.2	67.1	71.9	0	0	0	0
23	64.1	63.2	70.5	65.9	0	0	0	0	101.7	86.1	101.4	96.4	0	0	0	0
24	59.3	57.2	52.3	56.3	0	0	0	0	75.0	70.7	64.9	67.8	0	0	0	0
Overall	59.2				2				76.8				6			

Key:

Light Green – Average (mean) Times

Dark Green – Summation of Errors

Orange – Individual Accuracy Errors (highlighted for visibility)

Red w/ White Text – Indicates a system error during testing which invalidates that data point (program glitches, freezes, skipped pegs)

Yellow – Indicates a dropped peg during testing, however the data is still included in the dataset as it was not a system error.

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Table 14: Test Subject Raw Data – Hologram Method

Display Method	Holograms																	
Workstation Size	Small Board								Big Board									
Test Metric	Time (seconds)				Accuracy				Time (seconds)				Accuracy					
Test Subject #	Run #1	Run #2	Run #3	mean	Run #1	Run #2	Run #3	sum	Run #1	Run #2	Run #3	mean	Run #1	Run #2	Run #3	sum		
1	27.3	23.5	23.4	24.7	0	0	0	0	41.9	33.6	28.7	34.7	0	0	0	0		
2	25.4	24.0	22.1	23.8	0	0	0	0	31.8	32.3	33.4	32.5	0	0	0	0		
3	53.9	27.3	29.7	28.5	0	0	0	0	32.2	34.9	29.4	32.2	0	0	0	0		
4	27.2	26.8	27.7	27.2	0	0	0	0	37.3	37.3	34.8	36.4	0	0	0	0		
5	28.5	26.1	27.3	27.3	0	0	0	0	37.4	33.9	33.5	34.9	0	0	0	0		
6	27.2	26.5	24.5	26.1	0	0	0	0	35.7	34.9	37.3	35.9	0	0	0	0		
7	30.9	28.9	32.6	30.8	0	0	0	0	39.6	38.1	31.3	36.3	0	0	0	0		
8	30.9	28.9	27.5	29.1	0	0	0	0	36.3	47.4	36.3	36.3	0	0	0	0		
9	33.3	28.5	26.1	29.3	0	0	0	0	33.3	36.0	31.4	33.6	0	0	0	0		
10	41.4	35.2	36.8	37.8	0	0	0	0	55.2	48.5	56.6	53.4	0	0	0	0		
11	45.6	30.9	28.4	29.7	0	0	0	0	46.4	37.6	53.7	46.4	0	0	0	0		
12	31.4	21.4	20.9	24.5	0	0	0	0	27.6	28.5	26.1	27.4	0	0	0	0		
13	26.0	22.8	22.4	23.8	0	0	0	0	31.2	34.7	30.0	32.9	0	0	0	0		
14	45.2	41.6	39.7	42.1	0	0	0	0	38.6	56.0	53.2	56.0	0	0	0	0		
15	33.0	31.5	31.2	31.9	0	0	0	0	61.4	53.0	58.8	58.8	0	0	0	0		
16	43.3	37.5	35.9	38.9	0	0	0	0	49.0	52.0	47.3	49.4	0	0	0	0		
17	39.9	34.8	34.5	36.4	0	0	0	0	41.1	41.0	36.2	39.4	0	0	0	0		
18	48.3	34.6	28.4	31.5	0	0	0	0	53.0	46.3	53.6	51.0	0	0	0	0		
19	29.3	27.0	23.7	26.6	0	0	0	0	41.2	40.5	41.5	41.1	0	0	0	0		
20	28.6	25.5	22.9	25.7	0	0	0	0	41.3	37.9	40.9	40.1	0	0	0	0		
21	32.6	30.5	29.5	30.9	0	0	0	0	37.6	38.1	37.5	37.8	0	0	0	0		
22	29.4	25.7	22.4	25.8	0	0	0	0	41.4	33.1	35.5	36.6	0	0	0	0		
23	36.1	26.0	22.7	28.3	0	0	0	0	42.6	40.9	45.5	43.0	0	0	0	0		
24	41.3	37.6	35.9	38.2	0	0	0	0	40.7	44.8	39.1	41.5	0	0	0	0		
Overall				30.0					0				40.3					0

Key:

Light Green – Average (mean) Times

Dark Green – Summation of Errors

Orange – Individual Accuracy Errors (highlighted for viewability)

Red w/ White Text – Indicates a system error during testing which invalidates that data point (program glitches, freezes, skipped pegs)

Yellow – Indicates a dropped peg during testing, however the data is still included in the dataset as it was not a system error.

B.3 Performance Graphs

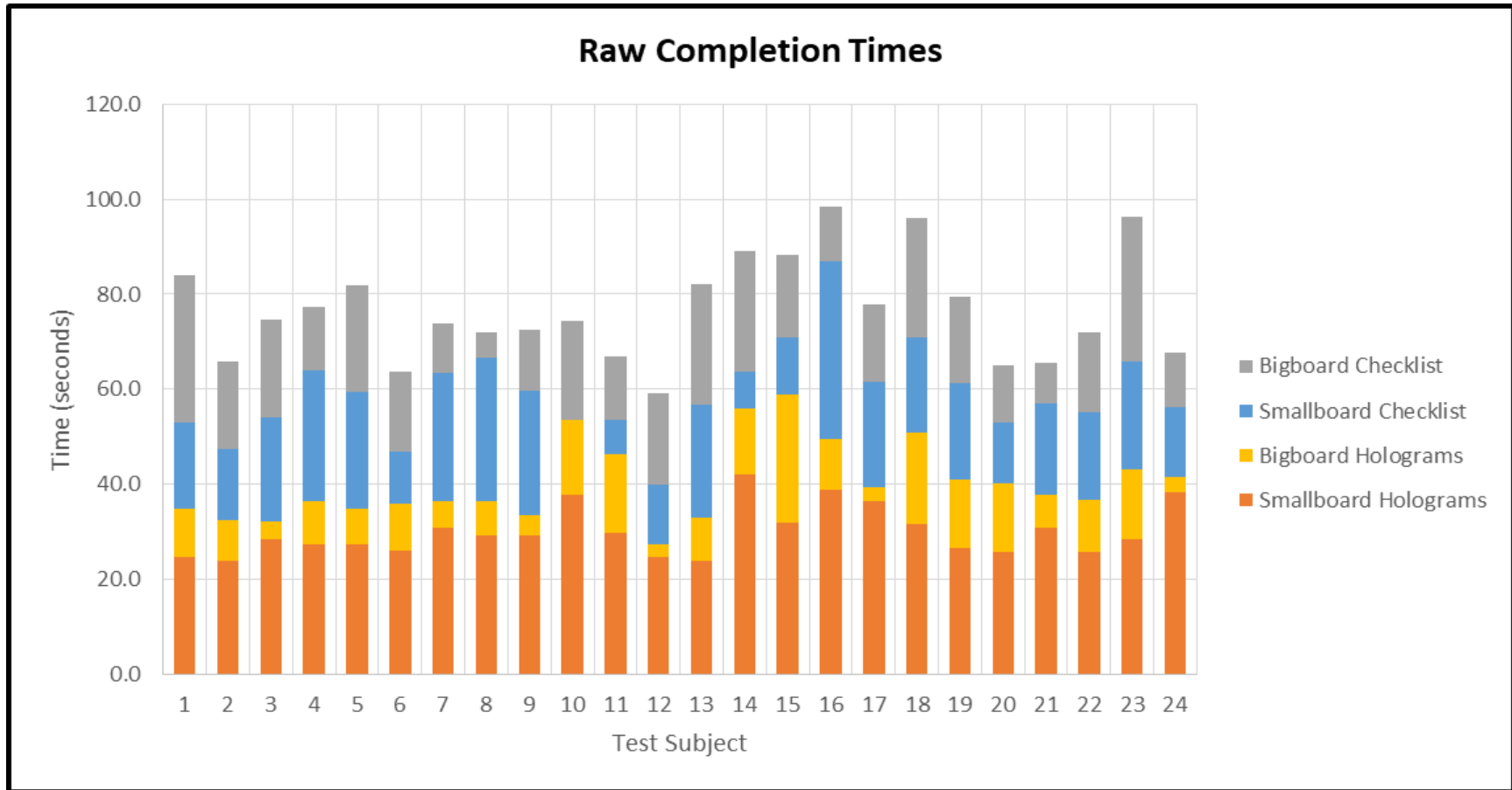


Figure 20: Raw Completion Times

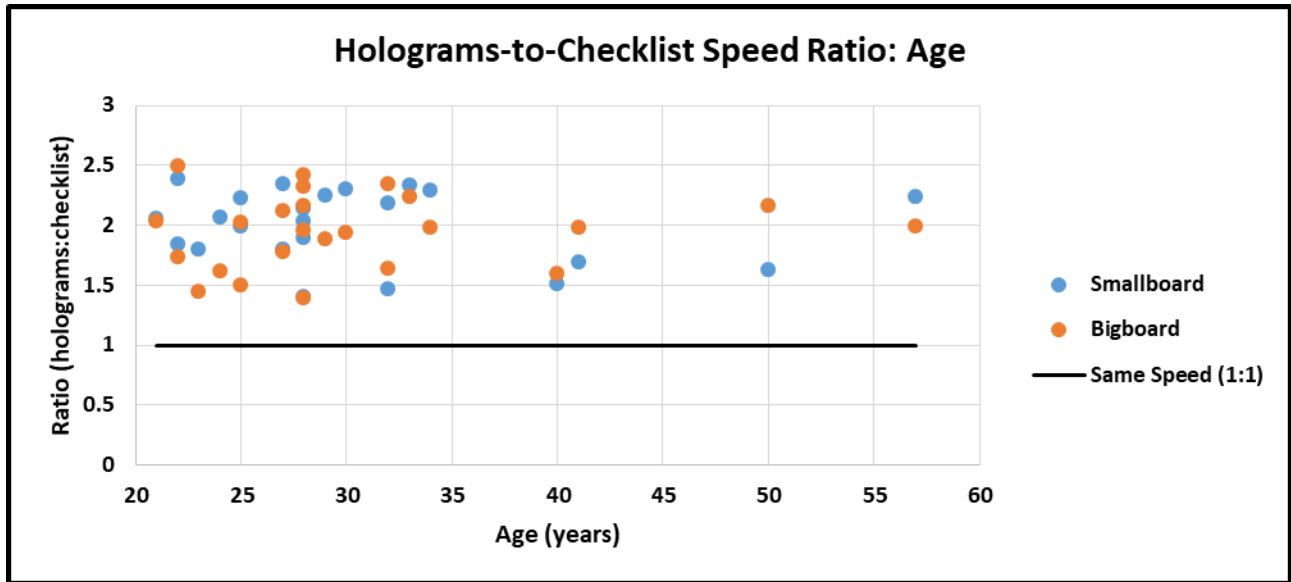


Figure 21: Speed Ratio vs. Subject Age

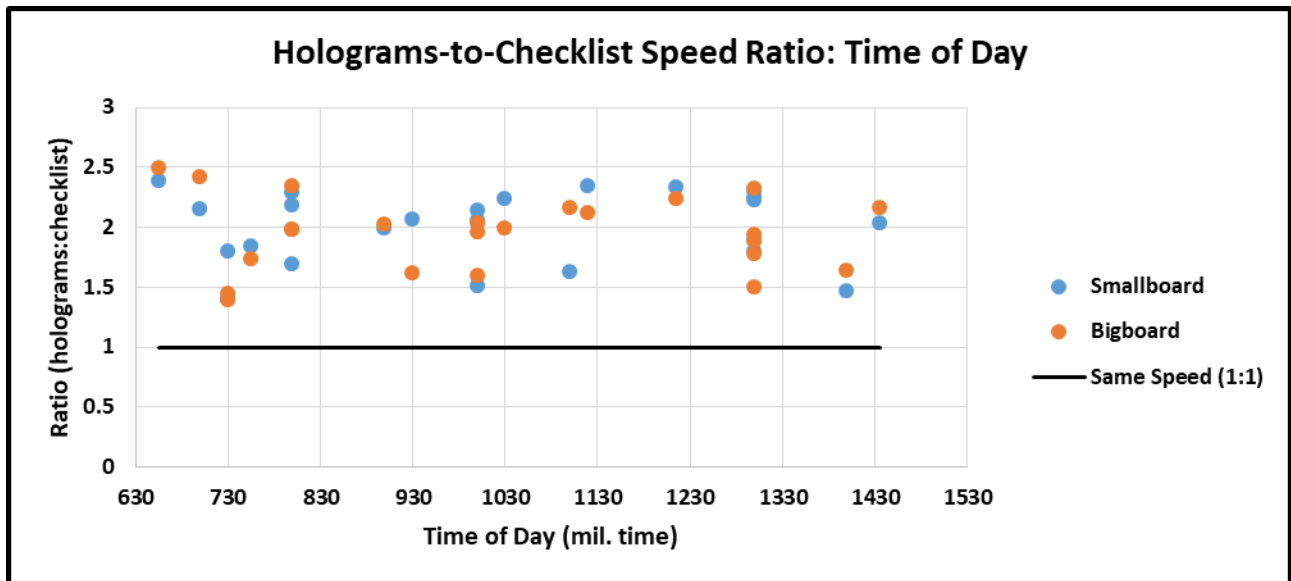


Figure 22: Speed Ratio vs. Time of Day

Subject age and the time of day of the test both appear to have little effect on the ratio of Hologram speed to Checklist speed (Figure 21 and 22)

On the following figures, the bar graph represents the average value of the subject population. The true average value for the representative population falls within the inner red margin with 95% confidence. 95% (2σ) of the representative population falls within the outer black margins. The number of subjects contained within each figure is given in the corresponding caption.

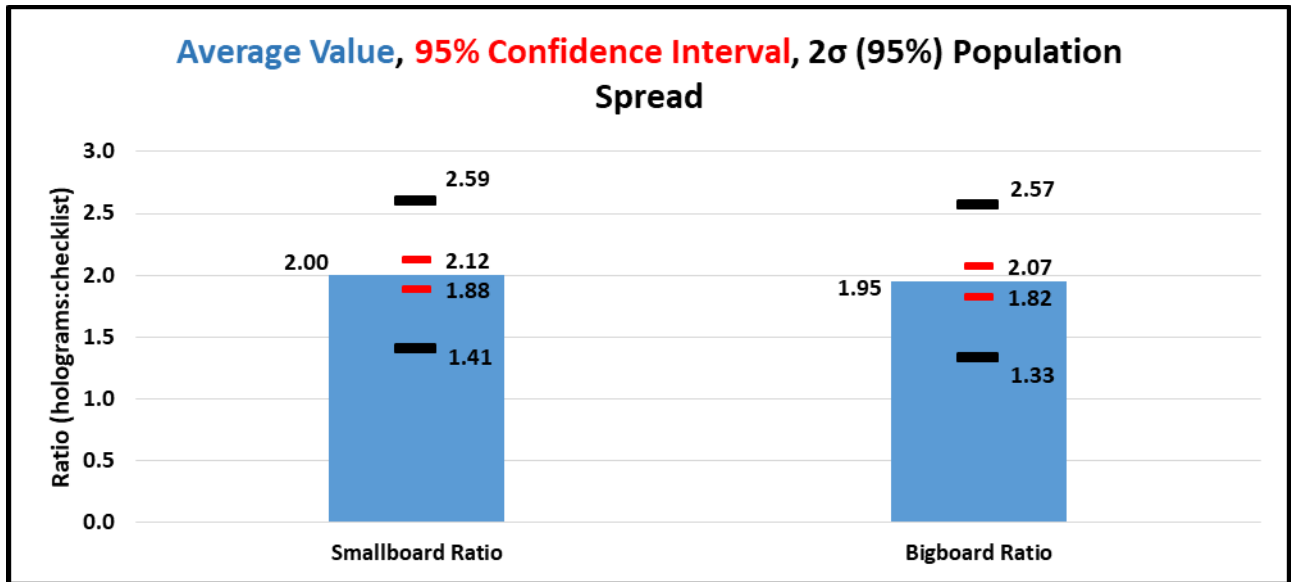


Figure 23: Entire Subject Population (n = 24)

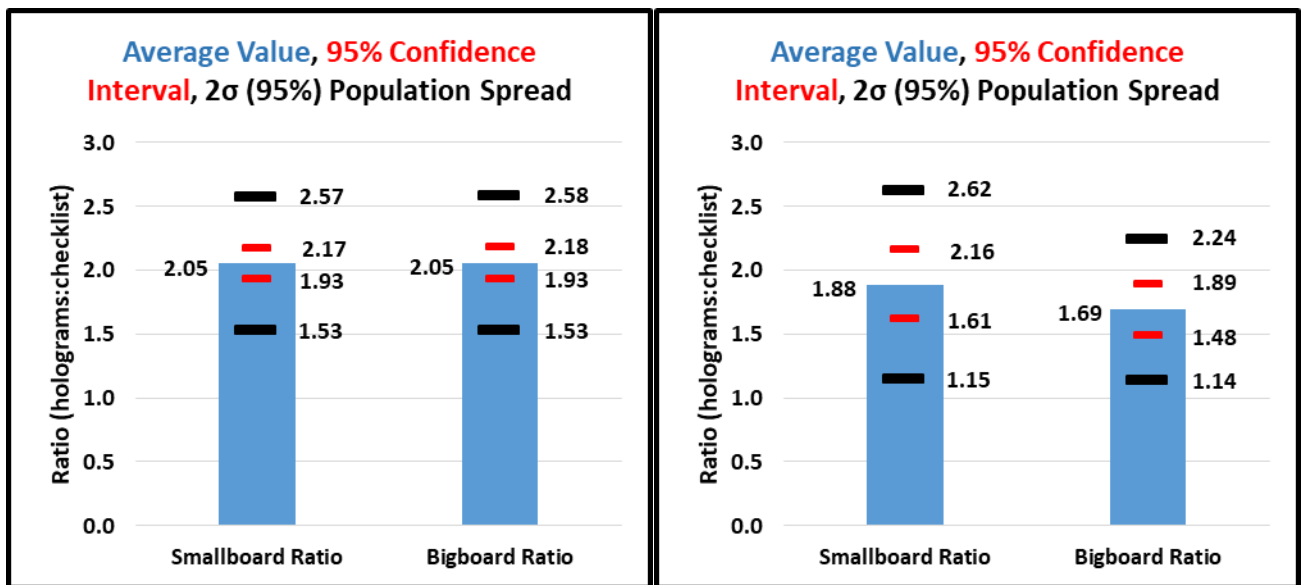


Figure 24: Male Subject Population (left, n = 17), Female Subject Population (right, n = 7)

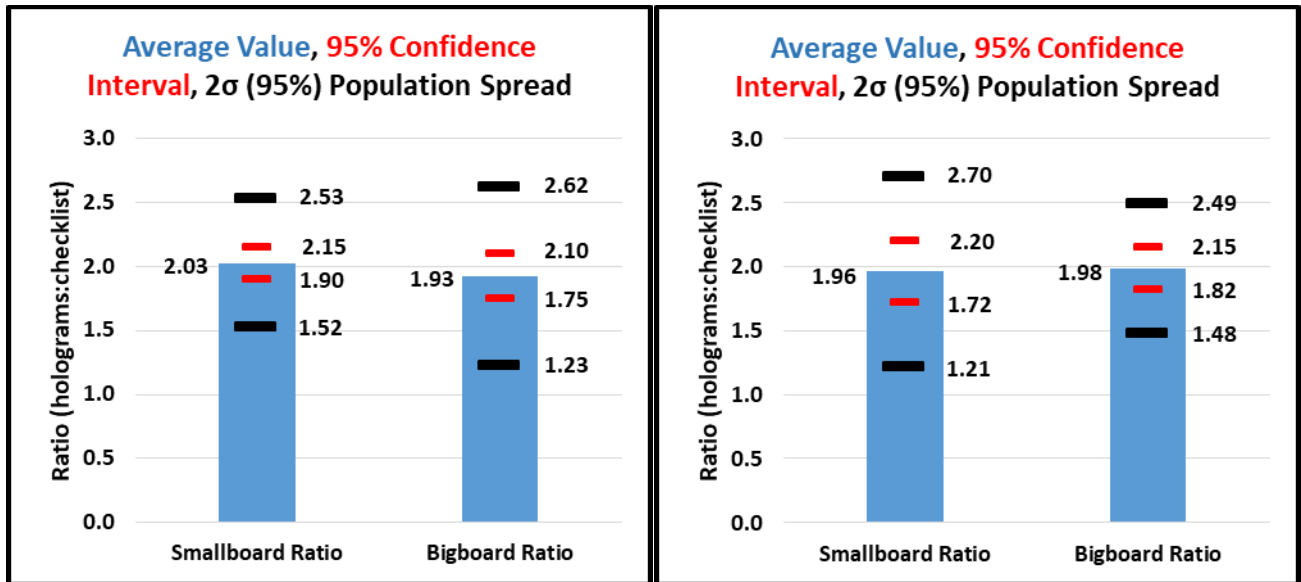


Figure 25: Under 30 Years Old (left, n = 15), 30 and Over (right, n = 9)

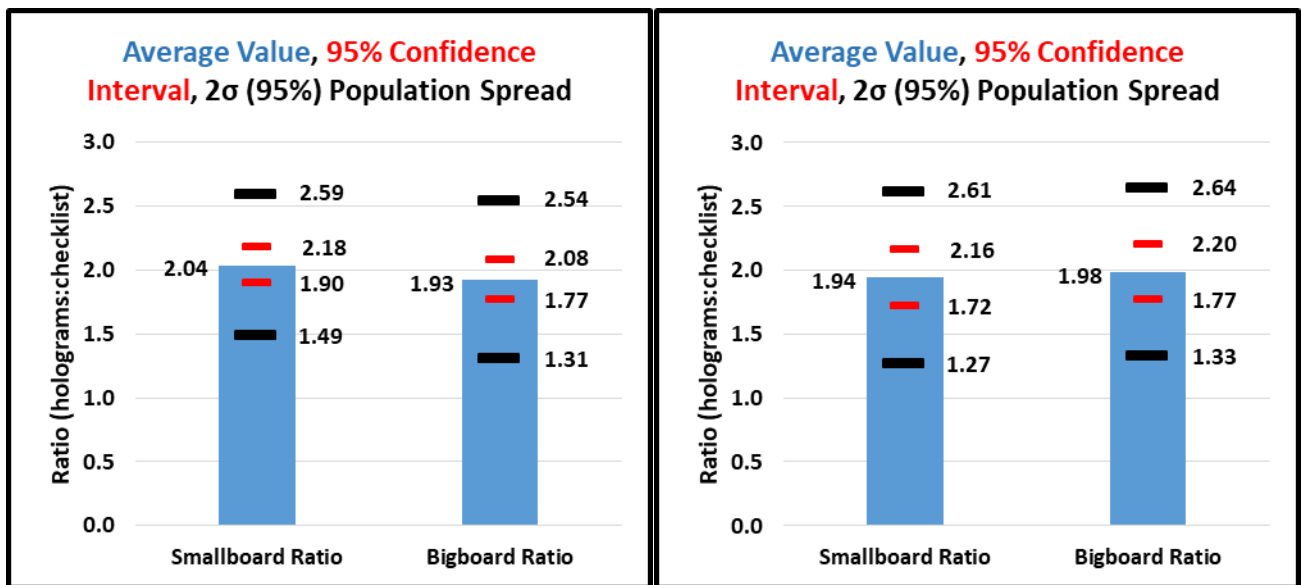


Figure 26: No Corrective Lenses (left, n = 15), Corrective Lenses (right, n = 9)

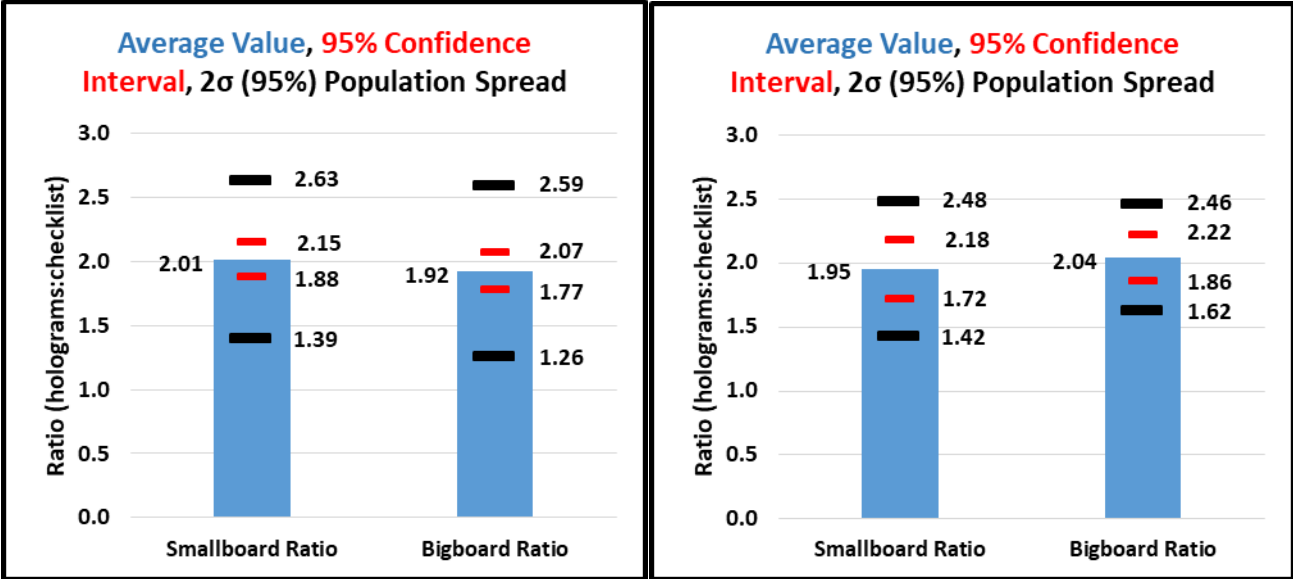


Figure 27: No/limited Experience (n = 19), Regular/Repeating Experience (n = 5)

B.4 Questionnaire Metrics

Subject #	Small Board List	Small Board Holograms	Big Board List	Big Board Holograms
1	2	5	1	3
2	4	5	3	4
3	2	5	1	4
4	4	5	2	5
5	3	5	2	4
6	4	5	4	5
7	4	5	1	5
8	5	5	3	5
9	2	3	1	4
10	5	5	3	4
11	5	5	4	5
12	4	5	3	4
13	4	5	4	5
14	3	5	2	4
15	5	5	3	4
16	4	5	3	5
17	3	5	1	4
18	2	4	1	5
19	3	5	2	5
20	3	4	2	5
21	5	5	5	5
22	3	5	2	5
23	5	5	5	5
24	3	5	2	4
Sum	87	116	60	108
Mean	3.63	4.83	2.50	4.50
Std	1.06	0.48	1.25	0.59

Appendix C: Computer Code

C.1 MATLAB Random Number Generator

(see 3.3.2 MATLAB 2017)

```
clear
close all
clc
%% ---- PEGBOARD STUDY RANDOM NUMBER GENERATOR --
--

% This script will generate a sequence of random
numbers for use with the
% developed Pegboard Study. Adjustable variables
are listed in the next
% section. Change these variables to match your
exact study layout.

% Many thanks go to Alex Raley for developing this
script on such short
% notice.

%% --- Adjustable variables ---
num_of_holes = 339;
num_of_runs = 6;
num_of_pegs = 50;
num_of_moves = 10;
hardcodestart = logical(0);

%% -----
initialpegs = randi([1 num_of_holes],
1,num_of_pegs);
```

```
ii= 0;
while ii < num_of_pegs
    ii = ii+1;
    if ii ==1
        pegs(ii) = initialpegs(ii);
    elseif find(pegs == initialpegs(ii))
        initialpegs(ii) = randi([1 num_of_holes],
1);
        ii = ii-1;
    else
        pegs(ii) = initialpegs(ii);
    end

end
all_peg_locations = initialpegs;
if length(unique(initialpegs)) ~= num_of_pegs
    disp('FAIL')
end
if hardcodestart
    clearvars -except num_of_moves num_of_pegs
num_of_sets num_of_holes initialpegs
    disp('alex')
    hardcode_start = initialpegs;
end
%% -----
for jj = 1:num_of_runs
    all_peg_locations(jj+1,:) =
all_peg_locations(jj, :);
    peg_to_move = randi([1, num_of_pegs],
1,num_of_moves);
    counter = 0;
    move = 1:num_of_holes;
    while length(unique(peg_to_move)) ~=num_of_moves
        peg_to_move = randi([1, num_of_pegs],
1,num_of_moves);
    end
```

```

for aa = 1:num_of_pegs
move(move == all_peg_locations(jj+1, aa)) = [];
end
moves = randi([1, length(move)], 1,num_of_moves);
while length(unique(moves)) ~=num_of_moves
moves = randi([1, length(move)], 1,num_of_moves);
end
%%
peg_movements{jj,3} = peg_to_move;
peg_movements{jj,2} = move(moves);

peg_movements{jj,1} = all_peg_locations(jj+1,
peg_to_move);

all_peg_locations(jj+1 , peg_to_move) =
move(moves);
end
%% -----
for jj = 1:num_of_runs
for ii =1:num_of_moves
if find(peg_movements{jj,1} ==
peg_movements{jj,2}(ii))
x(jj,ii) = peg_movements{jj,2}(ii);
disp('FAIL')
else
x(jj,ii) = 0;
end
end
end
end

```

C.2 Pegboard Study C# Script

```

using System.Collections;
using System.Collections.Generic;
using System;
//using System.Diagnostics;
//using System.Threading;
using System.IO;
using System.Linq;
using UnityEngine;
using UnityEngine.UI;
using UnityEngine.Windows.Speech;
using HoloToolkit.Unity.InputModule;
using UnityEngine.EventSystems;

public class buttons : MonoBehaviour, IInputClickHandler {

[Header("Txt Files")]
public TextAsset practiceBigtomove;
public TextAsset practiceBigwheretomove;
public TextAsset practiceSmalltomove;
public TextAsset practiceSmallwheretomove;
public TextAsset realBigtomove;
public TextAsset realBigwheretomove;
public TextAsset realSmalltomove;
public TextAsset realSmallwheretomove;

private KeywordRecognizer keywordRecognizer;
private Dictionary<string, System.Action> actions = new
Dictionary<string, System.Action>();

[Header("Prefabs")]
public GameObject pegtomoveprefab;
public GameObject placetomoveprefab;
public Vector3 PegPositionOffset;
public GameObject greenarrowprefab;
public GameObject redarrowprefab;
public GameObject ArrowPrefab1;
public GameObject CenterBoard;
public GameObject LeftBoard;
public GameObject RightBoard;
public GameObject TopBoard;

```

```
private GameObject ARcamera;
private GameObject cursor;
private GameObject pegboard;
private GameObject greenpeg;
private GameObject redpeg;
private GameObject green_arrow;
private GameObject green_arrow2;
private GameObject red_arrow2;
private GameObject orig_pos;
Transform loc;
```

```
[Header("Cursor")]
public GameObject CursorVisual;
```

```
private float greentheta;
private float redtheta;
```

```
private Vector3 temporary1;
private Vector3 temporary2;
private Vector3 temporary3;
private Vector3 temporary;
private Vector3 greenpegposAR;
private Vector3 greenpegangAR;
private Vector3 redpegposAR;
private Vector3 redpegangAR;
private Vector3 orig_posT;
private Vector3 orig_posR;
private Vector3 orig_posS;
private Vector3 newscale;
private Vector3 tweak;
private Vector3 scaledisplay;
private Vector3 handpos;
private Vector3 temp;
```

```
[Header("Buttons")]
public Button Practice_button;
public Button Test_button;
public Button BigBoard;
public Button BigBoard_list;
public Button BigBoard_AR;
public Button SmallBoard;
public Button SmallBoard_list;
public Button SmallBoard_AR;
public Button StartButton;
```

```
public Button NextmoveButton;
public Button backButton;
public Button ResetButton;
public Button PlusButton;
public Button MinusButton;
public Button ManualCalibration;
public Button zeropoint1;
public Button zeropointzero1;
public Button zeropointzerozero1;
public Button X;
public Button Y;
public Button Z;
public Button ExitCalibration;
public Button BoardView;
public Button TimeButton;
public Button ResetTimes;
public Button AreYouSure;
public Button VisionTest;
```

```
[Header("Texts")]
public Text tomovevxt;
public Text wheretomovetxt;
public Text wheretomoveboard;
public Text tomoveboard;
public Text movetxt;
public Text wheretomovetxt2;
public Text MoveCounterText;
public Text RunCounterText;
public Text TimeText;
public Text TimeText1;
public Text TimeText2;
public Text TimeText3;
public Text TimeText4;
public Text TimeText5;
public Text TimeText6;
public Text TimeText7;
public Text TimeText8;
public Text TimeText9;
public Text TimeText10;
public Text TimeText11;
public Text TimeText12;
public Text ScaleX;
public Text ScaleY;
public Text ScaleZ;
```

```

public Text VisionTestTextGreen;
public Text VisionTestTextRed;

[Header("Canvases")]
public Canvas tomovecanvas;
public Canvas wheretomovecanvas;
public Canvas MoveCounter;
public Canvas RunCounter;
public Canvas Scale;
public Canvas CurrentTime;
public Canvas TimeSeries;
public Canvas VisionTestCanvas;

[Header("Strings")]
public string[] Bigtomove;
public string[] Bigwheretomove;
public string[] Smalltomove;
public string[] Smallwheretomove;
string[] tomove;
string[] wheretomove;
string[] coordinatetomoveto;
string[] coordinatetomove;
private string axis;

[Header("Miscellaneous")]
public float timecount;
public int j = 0; // Run counter
public int Bigrows = 0; // Run counter for BigBoard runs
public int Smallrows = 0; // Run counter for SmallBoard runs
int numruns = 3; // number of Runs in one official test series
(for ex. BigBoard List).
// (cont'd) Must be a multiple of the total number of official
Test Runs
float arrowradius = 0.075f; // the distance from the cursor to
the center of the directional arrows
float green_periferal_check;
float red_periferal_check;
float timelength = 0.01f; // the time spacing for the time
counter (in seconds)
float top = -5.5f; // initial positioning for Vision Test text
items
float bottom = -7.5f; // initial positioning for Vision Test
text items
int a = 0;

```

```

int i = 0;
int k = 0;
int VisionTestCount = 1;

int[] pegstomove;
int[] placetomove;
int[] pegstomove2;
int[] placetomove2;
bool practice = false;
bool test = false;
bool bigboard = false;
bool smallboard = false;
bool ar = false;
bool list = false;
bool startcheck = false;
bool resetcheck = false;
bool calibrationcheck = false;
bool boardviewcheck = false;
bool timebuttoncheck = false;
bool resettimescheck = false;
bool visiontestcheck = false;
bool airtap;

void Start()
{
    ListType List = FindObjectOfType<ListType>();
    ARType AR = FindObjectOfType<ARType>();
    Practice_button.gameObject.SetActive(true);
    Test_button.gameObject.SetActive(true);
    TimeButton.gameObject.SetActive(true);
    VisionTest.gameObject.SetActive(true);
    practice = false;
    test = false;
    bigboard = false;
    smallboard = false;
    ar = false;
    list = false;
    startcheck = false;

    VisionTestCanvas.gameObject.SetActive(false);
    BigBoard.gameObject.SetActive(false);
    BigBoard_list.gameObject.SetActive(false);
    BigBoard_AR.gameObject.SetActive(false);
    SmallBoard.gameObject.SetActive(false);
}

```

```

SmallBoard_list.gameObject.SetActive(false);
SmallBoard_AR.gameObject.SetActive(false);
StartButton.gameObject.SetActive(false);
NextmoveButton.gameObject.SetActive(false);
wheretomovecanvas.gameObject.SetActive(false);
tomovecanvas.gameObject.SetActive(false);
backbutton.gameObject.SetActive(false);
ResetButton.gameObject.SetActive(false);
CursorVisual.gameObject.SetActive(true);
MoveCounter.gameObject.SetActive(false);
RunCounter.gameObject.SetActive(false);
PlusButton.gameObject.SetActive(false);
MinusButton.gameObject.SetActive(false);
ManualCalibration.gameObject.SetActive(true);
zeropoint1.gameObject.SetActive(false);
zeropointzero1.gameObject.SetActive(false);
zeropointzerozero1.gameObject.SetActive(false);
X.gameObject.SetActive(false);
Y.gameObject.SetActive(false);
Z.gameObject.SetActive(false);
Scale.gameObject.SetActive(false);
ExitCalibration.gameObject.SetActive(false);

actions.Add("go back", back);

actions.Add("move forward", Forward);
actions.Add("move backward", Backward);
actions.Add("move right", Right);
actions.Add("move left", Left);
actions.Add("move up", Up);
actions.Add("move down", Down);
actions.Add("roll right", RollRight);
actions.Add("roll left", RollLeft);
actions.Add("pitch up", PitchUp);
actions.Add("pitch down", PitchDown);
actions.Add("yaw right", YawRight);
actions.Add("yaw left", YawLeft);
actions.Add("reset position", Resetpos);
actions.Add("reset rotation", Resetrot);
actions.Add("reset scale", Resetsca);

keywordRecognizer = new
KeywordRecognizer(actions.Keys.ToArray());
keywordRecognizer.OnPhraseRecognized += RecognizedSpeech;

```

```

keywordRecognizer.Start();

pegboard = GameObject.Find("Pegboard");
ARcamera = GameObject.Find("ARCamera");
cursor = GameObject.Find("DefaultCursor");

if (resetcheck == false)
{
    // these things only happen when the program FIRST
STARTS UP
    orig_posT.x = pegboard.transform.localPosition.x;
    orig_posT.y = pegboard.transform.localPosition.y;
    orig_posT.z = pegboard.transform.localPosition.z;
    orig_posR.x = pegboard.transform.localEulerAngles.x;
    orig_posR.y = pegboard.transform.localEulerAngles.y;
    orig_posR.z = pegboard.transform.localEulerAngles.z;
    orig_posS.x = pegboard.transform.localScale.x;
    orig_posS.y = pegboard.transform.localScale.y;
    orig_posS.z = pegboard.transform.localScale.z;
    CenterBoard.gameObject.SetActive(false);
    LeftBoard.gameObject.SetActive(false);
    RightBoard.gameObject.SetActive(false);
    TopBoard.gameObject.SetActive(false);
    resetcheck = true;
    CurrentTime.gameObject.SetActive(false);
    TimeSeries.gameObject.SetActive(false);
    ResetTimes.gameObject.SetActive(false);
    AreYouSure.gameObject.SetActive(false);
}
}

private void RecognizedSpeech(PhraseRecognizedEventArgs speech)
{
    actions[speech.text].Invoke();
}

private void back()
{
    if (practice == false && test == false)
        return;

    Back();
}

```

```

float translatedelta = 6 * 0.0254f;
int rotatedelta = 10;

void Resetpos()
{
    if (calibrationcheck == true)
        transform.localPosition = orig_posT;
}
void Resetrot()
{
    if (calibrationcheck == true)
        transform.localEulerAngles = orig_posR;
}
void Resetsca()
{
    if (calibrationcheck == true)
        transform.localScale = orig_posS;
}

void Forward()
{
    if (calibrationcheck == true)
        transform.Translate(0, translatedelta, 0);
}
void Backward()
{
    if (calibrationcheck == true)
        transform.Translate(0, -translatedelta, 0);
}
void Up()
{
    if (calibrationcheck == true)
        transform.Translate(0, 0, translatedelta);
}
void Down()
{
    if (calibrationcheck == true)
        transform.Translate(0, 0, -translatedelta);
}
void Right()
{
    if (calibrationcheck == true)
        transform.Translate(translatedelta, 0, 0);
}

```

```

void Left()
{
    if (calibrationcheck == true)
        transform.Translate(-translatedelta, 0, 0);
}
void RollRight()
{
    if (calibrationcheck == true)
        transform.Rotate(0, rotatedelta, 0);
}
void RollLeft()
{
    if (calibrationcheck == true)
        transform.Rotate(0, -rotatedelta, 0);
}
void PitchUp()
{
    if (calibrationcheck == true)
        transform.Rotate(-rotatedelta, 0, 0);
}
void PitchDown()
{
    if (calibrationcheck == true)
        transform.Rotate(rotatedelta, 0, 0);
}
void YawRight()
{
    if (calibrationcheck == true)
        transform.Rotate(0, 0, rotatedelta);
}
void YawLeft()
{
    if (calibrationcheck == true)
        transform.Rotate(0, 0, -rotatedelta);
}

void Update()
{
    if (bigboard == true && ar == true && startcheck == true)
    {
        greenpeg.transform.parent = ARcamera.transform;
        greenpegposAR = greenpeg.transform.localPosition;
        greenpegangAR = greenpeg.transform.localEulerAngles;
    }
}

```



```

Bigwheretomove = txt1.Split('\n');
string txt2 = practiceSmalltomove.ToString();
Smalltomove = txt2.Split('\n');
string txt3 = practiceSmallwheretomove.ToString();
Smallwheretomove = txt3.Split('\n');
if (Bigrows < Bigtomove.Length)
{
    BigBoard.gameObject.SetActive(true);
}
if (Smallrows < Smalltomove.Length)
{
    SmallBoard.gameObject.SetActive(true);
}
backbutton.gameObject.SetActive(true);
ResetButton.gameObject.SetActive(true);
}

```

```

public void Test()
{
    practice = false;
    test = true;
    Practice_button.gameObject.SetActive(false);
    Test_button.gameObject.SetActive(false);
    VisionTest.gameObject.SetActive(false);
    CursorVisual.gameObject.SetActive(true);
    string txt = realBigtomove.ToString();
    Bigtomove = txt.Split('\n');
    string txt1 = realBigwheretomove.ToString();
    Bigwheretomove = txt1.Split('\n');
    string txt2 = realSmalltomove.ToString();
    Smalltomove = txt2.Split('\n');
    string txt3 = realSmallwheretomove.ToString();
    Smallwheretomove = txt3.Split('\n');
    if (Bigrows < Bigtomove.Length)
    {
        BigBoard.gameObject.SetActive(true);
    }
    if (Smallrows < Smalltomove.Length)
    {
        SmallBoard.gameObject.SetActive(true);
    }
    backbutton.gameObject.SetActive(true);
    ResetButton.gameObject.SetActive(true);
}

```

```

}

public void Small()
{
    smallboard = true;
    bigboard = false;
    SmallBoard.gameObject.SetActive(false);
    BigBoard.gameObject.SetActive(false);
    SmallBoard_list.gameObject.SetActive(true);
    SmallBoard_AR.gameObject.SetActive(true);
    j = Smallrows;
}

public void Big()
{
    bigboard = true;
    smallboard = false;
    BigBoard_list.gameObject.SetActive(true);
    BigBoard_AR.gameObject.SetActive(true);
    SmallBoard.gameObject.SetActive(false);
    BigBoard.gameObject.SetActive(false);
    j = Bigrows;
}

public void Small_List()
{
    list = true;
    SmallBoard_AR.gameObject.SetActive(false);
    SmallBoard_list.gameObject.SetActive(false);
    StartButton.gameObject.SetActive(true);
    CursorVisual.gameObject.SetActive(true);
    MoveCounter.gameObject.SetActive(false);
    tomove = Smalltomove;
    wheretomove = Smallwheretomove;
    RunCounter.gameObject.SetActive(true);
    string jString = (j + 1).ToString();
    RunCounterText.text = jString;
    PlusButton.gameObject.SetActive(true);
    MinusButton.gameObject.SetActive(true);
}

```

```

public void Smallboard_AR()
{
    ar = true;
    SmallBoard_AR.gameObject.SetActive(false);
    SmallBoard_list.gameObject.SetActive(false);
    StartButton.gameObject.SetActive(true);
    CursorVisual.gameObject.SetActive(true);
    MoveCounter.gameObject.SetActive(false);
    tomove = Smalltomove;
    wheretomove = Smallwheretomove;
    RunCounter.gameObject.SetActive(true);
    string jString = (j + 1).ToString();
    RunCounterText.text = jString;
    PlusButton.gameObject.SetActive(true);
    MinusButton.gameObject.SetActive(true);
}

public void Big_List()
{
    list = true;
    BigBoard_AR.gameObject.SetActive(false);
    BigBoard_list.gameObject.SetActive(false);
    StartButton.gameObject.SetActive(true);
    CursorVisual.gameObject.SetActive(true);
    MoveCounter.gameObject.SetActive(false);
    tomove = Bigtomove;
    wheretomove = Bigwheretomove;
    RunCounter.gameObject.SetActive(true);
    string jString = (j + 1).ToString();
    RunCounterText.text = jString;
    PlusButton.gameObject.SetActive(true);
    MinusButton.gameObject.SetActive(true);
}

public void Bigboard_AR()
{
    ar = true;
    BigBoard_AR.gameObject.SetActive(false);
    BigBoard_list.gameObject.SetActive(false);
    StartButton.gameObject.SetActive(true);
    CursorVisual.gameObject.SetActive(true);
    MoveCounter.gameObject.SetActive(false);
    tomove = Bigtomove;
    wheretomove = Bigwheretomove;
    RunCounter.gameObject.SetActive(true);
    string jString = (j + 1).ToString();
    RunCounterText.text = jString;
    PlusButton.gameObject.SetActive(true);
    MinusButton.gameObject.SetActive(true);
}

MoveCounter.gameObject.SetActive(false);
tomove = Bigtomove;
wheretomove = Bigwheretomove;
RunCounter.gameObject.SetActive(true);
string jString = (j + 1).ToString();
RunCounterText.text = jString;
PlusButton.gameObject.SetActive(true);
MinusButton.gameObject.SetActive(true);
}

public void plus_button()
{
    if (test == true)
    {
        if (j < 5)
        {
            j++;
            string jString = (j + 1).ToString();
            RunCounterText.text = jString;
        }
    }
    else if (practice == true)
    {
        if (j < 29)
        {
            j++;
            string jString = (j + 1).ToString();
            RunCounterText.text = jString;
        }
    }
    if (calibrationcheck == true)
    {
        newscale = pegboard.transform.localScale + tweak;
        pegboard.transform.localScale = newscale;

        double round =
        Math.Round(pegboard.transform.localScale.x, 4);
        scaledisplay.x = (float)round;
        round = Math.Round(pegboard.transform.localScale.y, 4);
        scaledisplay.y = (float)round;
        round = Math.Round(pegboard.transform.localScale.z, 4);
        scaledisplay.z = (float)round;
    }
}

```

```

        string ScaleXString = scaledisplay.x.ToString();
        string ScaleYString = scaledisplay.y.ToString();
        string ScaleZString = scaledisplay.z.ToString();
        ScaleX.text = ScaleXString;
        ScaleY.text = ScaleYString;
        ScaleZ.text = ScaleZString;
    }
}

public void minus_button()
{
    if (j != 0)
    {
        j--;
        string jString = (j + 1).ToString();
        RunCounterText.text = jString;
    }
    if (calibrationcheck == true)
    {
        newscale = pegboard.transform.localScale - tweak;
        pegboard.transform.localScale = newscale;

        double round =
Math.Round(pegboard.transform.localScale.x, 4);
        scaledisplay.x = (float)round;
        round = Math.Round(pegboard.transform.localScale.y, 4);
        scaledisplay.y = (float)round;
        round = Math.Round(pegboard.transform.localScale.z, 4);
        scaledisplay.z = (float)round;
        string ScaleXString = scaledisplay.x.ToString();
        string ScaleYString = scaledisplay.y.ToString();
        string ScaleZString = scaledisplay.z.ToString();
        ScaleX.text = ScaleXString;
        ScaleY.text = ScaleYString;
        ScaleZ.text = ScaleZString;
    }
}

public void begin()
{
    ResetButton.gameObject.SetActive(false);
    StartButton.gameObject.SetActive(false);

```

```

MoveCounter.gameObject.SetActive(true);
RunCounter.gameObject.SetActive(false);
PlusButton.gameObject.SetActive(false);
MinusButton.gameObject.SetActive(false);
CurrentTime.gameObject.SetActive(false);
TimeButton.gameObject.SetActive(false);
ResetTimes.gameObject.SetActive(false);
AreYouSure.gameObject.SetActive(false);
TimeSeries.gameObject.SetActive(false);
timebuttoncheck = false;
resettimescheck = false;
pegstomove = ARType.StringToArray(tomove[j], ",");
placestomove = ARType.StringToArray(wheretomove[j], ",");

if (bigboard == true && ar == true)
    CursorVisual.gameObject.SetActive(false);

if (ar == true)
{
    pegstomove2 = ARType.pegstart(pegstomove[i]);
    placestomove2 = ARType.pegmove(placestomove[i]);

    move(pegstomove2[0], pegstomove2[1], pegstomove2[2]);
    movehere(placestomove2[0], placestomove2[1],
placestomove2[2]);

    if (bigboard == true)
    {
        green_arrow2 =
(GameObject)Instantiate(greenarrowprefab);
        green_arrow2.transform.parent = ARcamera.transform;
        green_arrow2.transform.position =
ARcamera.transform.position;
        green_arrow2.transform.localPosition += new
Vector3(0f, 0f, 0.5f);

        red_arrow2 = (GameObject)Instantiate(redarrowprefab);
        red_arrow2.transform.parent = ARcamera.transform;
        red_arrow2.transform.position =
ARcamera.transform.position;
        red_arrow2.transform.localPosition += new Vector3(0f,
0f, 0.5f);
    }
}

```

```

        i++;
        string iString = i.ToString();
        MoveCounterText.text = iString;
    }
    else if (list == true)
    {
        if (GameObject.Find("pegtomoveprefab(Clone)") ||
        GameObject.Find("placetomoveprefab(Clone)"))
        {
            Destroy(GameObject.Find("pegtomoveprefab(Clone)"));
            Destroy(GameObject.Find("placetomoveprefab(Clone)"));
            Destroy(green_arrow);
            Destroy(green_arrow2);
            Destroy(red_arrow2);
        }
        wheretomovecanvas.gameObject.SetActive(true);
        tomovecanvas.gameObject.SetActive(true);
        ListType List = FindObjectOfType<ListType>();
        coordinatetomove = List.Getcoordinates(pegstomove[i]);
        coordinatetomoveto =
        List.Getcoordinates(placetomove[i]);
        i++;
        string iString = i.ToString();
        MoveCounterText.text = iString;

        tomoveboard.text = coordinatetomove[0];
        tomovetxt.text = coordinatetomove[1] +
        coordinatetomove[2];
        wheretomoveboard.text = coordinatetomoveto[0];
        wheretomovetxt.text = coordinatetomoveto[1] +
        coordinatetomoveto[2];
    }
    NextmoveButton.gameObject.SetActive(true);

    timecount = 0f;
    InvokeRepeating("Timer", 0f, timelength);

    Invoke("StartCheck", .01f); // delay 0.01 second before
    switching startcheck to true.
    return; // This prevents "OnInputClicked"
    (see bottom) from clicking
    } // simultaneously while clicking the start
    button, causing two clicks to occur.

```

```

public void Next()
{
    if (GameObject.Find("pegtomoveprefab(Clone)") ||
    GameObject.Find("placetomoveprefab(Clone)"))
    {
        Destroy(GameObject.Find("pegtomoveprefab(Clone)"));
        Destroy(GameObject.Find("placetomoveprefab(Clone)"));
        Destroy(green_arrow);
        Destroy(green_arrow2);
        Destroy(red_arrow2);
    }
    if (i + 1 > pegstomove.Length)
    {
        CancelInvoke();
        timecount = (float)Math.Round(timecount, 2);
        string timecountstring = timecount.ToString();
        TimeText.text = timecountstring;
        TimeButton.gameObject.SetActive(true);
        k++;
        if (k == 1)
            TimeText1.text = timecountstring;
        else if (k == 2)
            TimeText2.text = timecountstring;
        else if (k == 3)
            TimeText3.text = timecountstring;
        else if (k == 4)
            TimeText4.text = timecountstring;
        else if (k == 5)
            TimeText5.text = timecountstring;
        else if (k == 6)
            TimeText6.text = timecountstring;
        else if (k == 7)
            TimeText7.text = timecountstring;
        else if (k == 8)
            TimeText8.text = timecountstring;
        else if (k == 9)
            TimeText9.text = timecountstring;
        else if (k == 10)
            TimeText10.text = timecountstring;
        else if (k == 11)
            TimeText11.text = timecountstring;
        else if (k == 12)
            TimeText12.text = timecountstring;
    }
}

```

```

i = 0;
j++;

if (test == true && j % numruns != 0)
{
    PlusButton.gameObject.SetActive(true);
    MinusButton.gameObject.SetActive(true);
    RunCounter.gameObject.SetActive(true);
    string jString = (j + 1).ToString();
    RunCounterText.text = jString;
}

StartButton.gameObject.SetActive(true);
CursorVisual.gameObject.SetActive(true);
startcheck = false;
NextmoveButton.gameObject.SetActive(false);
ResetButton.gameObject.SetActive(false);
wheretomovecanvas.gameObject.SetActive(false);
tomovecanvas.gameObject.SetActive(false);
MoveCounter.gameObject.SetActive(false);
if (bigboard == true)
{
    Bigrows = j;
}
else if (smallboard == true)
{
    Smallrows = j;
}

if (Bigrows >= Bigtomove.Length && Smallrows >=
Smalltomove.Length)
{
    Reset();
    return;
}
else if ((list == true && j % numruns == 0) || list ==
true && practice == true)
{
    list = false;
    smallboard = false;
    bigboard = false;
    wheretomovecanvas.gameObject.SetActive(false);
    tomovecanvas.gameObject.SetActive(false);

    StartButton.gameObject.SetActive(false);
    ResetButton.gameObject.SetActive(true);
    CursorVisual.gameObject.SetActive(true);
    MoveCounter.gameObject.SetActive(false);
    if (Bigrows < Bigtomove.Length)
    {
        BigBoard.gameObject.SetActive(true);
    }
    if (Smallrows < Smalltomove.Length)
    {
        SmallBoard.gameObject.SetActive(true);
    }
    return;
}
else if ((ar == true && j % numruns == 0) || ar == true
&& practice == true)
{
    ar = false;
    smallboard = false;
    bigboard = false;
    StartButton.gameObject.SetActive(false);
    ResetButton.gameObject.SetActive(true);
    CursorVisual.gameObject.SetActive(true);
    MoveCounter.gameObject.SetActive(false);
    if (Bigrows < Bigtomove.Length)
    {
        BigBoard.gameObject.SetActive(true);
    }
    if (Smallrows < Smalltomove.Length)
    {
        SmallBoard.gameObject.SetActive(true);
    }
    return;
}
}
else if (ar == true)
{
    pegstomove2 = ARType.pegstart(pegstomove[i]);
    placestomove2 = ARType.pegmove(placestomove[i]);

    move(pegstomove2[0], pegstomove2[1], pegstomove2[2]);
    movehere(placestomove2[0], placestomove2[1],
placestomove2[2]);
    if (bigboard == true)

```

```

        {
            /*// green_arrow creates a 3D floating arrow which is
            spatially // fixed in front of the headset, but points at the
            target (in 3 dimensions) // (not sure if it still works currently, may have
            deleted something)
            green_arrow =
            (GameObject)Instantiate(greenarrowprefab);
            green_arrow.transform.parent = ARcamera.transform;
            green_arrow.transform.position =
            ARcamera.transform.position;
            green_arrow.transform.localPosition += new
            Vector3(0f, 0f, 0.5f);*/

            green_arrow2 =
            (GameObject)Instantiate(greenarrowprefab);
            green_arrow2.transform.parent = ARcamera.transform;
            green_arrow2.transform.position =
            ARcamera.transform.position;
            green_arrow2.transform.localPosition += new
            Vector3(0f, 0f, 0.5f);

            red_arrow2 = (GameObject)Instantiate(redarrowprefab);
            red_arrow2.transform.parent = ARcamera.transform;
            red_arrow2.transform.position =
            ARcamera.transform.position;
            red_arrow2.transform.localPosition += new Vector3(0f,
            0f, 0.5f);

        }
        i++;
        string iString = i.ToString();
        MoveCounterText.text = iString;
    }
    else if (list == true)
    {
        wheretomovecanvas.gameObject.SetActive(true);
        tomovecanvas.gameObject.SetActive(true);
        ListType List = FindObjectOfType<ListType>();
        coordinatetomove = List.Getcoordinates(pegstomove[i]);
        coordinatetomoveto =
        List.Getcoordinates(placestomove[i]);
    }

```

```

        i++;
        string iString = i.ToString();
        MoveCounterText.text = iString;

        tomoveboard.text = coordinatetomove[0];
        tomovetxt.text = coordinatetomove[1] +
        coordinatetomove[2];
        wheretomoveboard.text = coordinatetomoveto[0];
        wheretomovetxt.text = coordinatetomoveto[1] +
        coordinatetomoveto[2];
    }
    return;
}

public void Reset()
{
    practice = false;
    test = false;
    bigboard = false;
    smallboard = false;
    ar = false;
    list = false;
    startcheck = false;
    Bigrows = 0;
    Smallrows = 0;
    j = 0;
    i = 0;
    a = 0;
    if (GameObject.Find("pegtomoveprefab(Clone)") ||
    GameObject.Find("placetomoveprefab(Clone)"))
    {
        Destroy(GameObject.Find("pegtomoveprefab(Clone)"));
        Destroy(GameObject.Find("placetomoveprefab(Clone)"));
        Destroy(green_arrow);
        Destroy(green_arrow2);
        Destroy(red_arrow2);
    }
    Start();
}

public void Back()

```

```

{
    if (practice == true)
    {
        if (bigboard == true)
        {
            if (ar == true)
            {
                if (startcheck == true)
                {
                    if (i == 1)
                    {
                        Destroy(GameObject.Find("pegtomoveprefab(Clone)"));
                        Destroy(GameObject.Find("placetomoveprefab(Clone)"));
                        Destroy(green_arrow);
                        Destroy(green_arrow2);
                        Destroy(red_arrow2);
                        i = 0;

                        NextmoveButton.gameObject.SetActive(false);
                        ResetButton.gameObject.SetActive(true);
                        TimeButton.gameObject.SetActive(true);
                        CancelInvoke();
                        startcheck = false;
                        Bigboard_AR();
                        return;
                    }
                }
            }
            else if (i > 1)
            {
                a = i - 2;
                i = a;
                Next();
                return;
            }
        }
    }
    else if (startcheck == false)
    {
        if (calibrationcheck == false)
        {
            PlusButton.gameObject.SetActive(false);
            MinusButton.gameObject.SetActive(false);
        }
        StartButton.gameObject.SetActive(false);

        RunCounter.gameObject.SetActive(false);
        ar = false;
        Big();
        return;
    }
}
else if (list == true)
{
    if (startcheck == true)
    {
        if (i == 1)
        {
            wheretomovecanvas.gameObject.SetActive(false);
            tomovecanvas.gameObject.SetActive(false);
            i = 0;

            NextmoveButton.gameObject.SetActive(false);
            ResetButton.gameObject.SetActive(true);
            TimeButton.gameObject.SetActive(true);
            CancelInvoke();
            startcheck = false;
            Big_List();
            return;
        }
        else if (i > 1)
        {
            a = i - 2;
            i = a;
            Next();
            return;
        }
    }
    else if (startcheck == false)
    {
        if (calibrationcheck == false)
        {
            PlusButton.gameObject.SetActive(false);
            MinusButton.gameObject.SetActive(false);
        }
        RunCounter.gameObject.SetActive(false);
        StartButton.gameObject.SetActive(false);
        list = false;
        Big();
    }
}
}

```

```

        return;
    }
}
else if (ar == false && list == false)
{
    BigBoard_list.gameObject.SetActive(false);
    BigBoard_AR.gameObject.SetActive(false);
    bigboard = false;
    Practice();
    return;
}
}
else if (smallboard == true)
{
    if (ar == true)
    {
        if (startcheck == true)
        {
            if (i == 1)
            {
                Destroy(GameObject.Find("pegtomoveprefab(Clone)"));

                Destroy(GameObject.Find("placetomoveprefab(Clone)"));
                Destroy(green_arrow);
                Destroy(green_arrow2);
                Destroy(red_arrow2);
                i = 0;

                NextmoveButton.gameObject.SetActive(false);
                TimeButton.gameObject.SetActive(true);
                ResetButton.gameObject.SetActive(true);
                CancelInvoke();
                startcheck = false;
                Smallboard_AR();
            }
            else if (i > 1)
            {
                a = i - 2;
                i = a;
                Next();
            }
        }
        else if (startcheck == false)

```

```

    {
        if (calibrationcheck == false)
        {
            PlusButton.gameObject.SetActive(false);
            MinusButton.gameObject.SetActive(false);
        }
        RunCounter.gameObject.SetActive(false);
        StartButton.gameObject.SetActive(false);
        ar = false;
        Small();
        return;
    }
}
if (list == true)
{
    if (startcheck == true)
    {
        if (i == 1)
        {
            wheretomovecanvas.gameObject.SetActive(false);
            tomovecanvas.gameObject.SetActive(false);
            i = 0;

            NextmoveButton.gameObject.SetActive(false);
            TimeButton.gameObject.SetActive(true);
            ResetButton.gameObject.SetActive(true);
            CancelInvoke();
            startcheck = false;
            Small_List();
            return;
        }
        else if (i > 1)
        {
            a = i - 2;
            i = a;
            Next();
            return;
        }
    }
    else if (startcheck == false)
    {
        if (calibrationcheck == false)
        {

```

```

        PlusButton.gameObject.SetActive(false);
        MinusButton.gameObject.SetActive(false);
    }
    RunCounter.gameObject.SetActive(false);
    StartButton.gameObject.SetActive(false);
    list = false;
    Small();
    return;
}
}
else if (ar == false && list == false)
{
    SmallBoard_list.gameObject.SetActive(false);
    SmallBoard_AR.gameObject.SetActive(false);
    smallboard = false;
    Practice();
    return;
}
}
else if (bigboard == false && smallboard == false)
{
    practice = false;
    Start();
    return;
}
}
if (test == true)
{
    if (bigboard == true)
    {
        if (ar == true)
        {
            if (startcheck == true)
            {
                if (i == 1)
                {
                    Destroy(GameObject.Find("pegtomoveprefab(Clone)"));
                    Destroy(GameObject.Find("placetomoveprefab(Clone)"));
                    Destroy(green_arrow);
                    Destroy(green_arrow2);
                    Destroy(red_arrow2);
                    i = 0;
                }
            }
        }
    }
}

```

```

NextmoveButton.gameObject.SetActive(false);
    TimeButton.gameObject.SetActive(true);
    ResetButton.gameObject.SetActive(true);
    CancelInvoke();
    startcheck = false;
    Bigboard_AR();
    return;
}
else if (i > 1)
{
    a = i - 2;
    i = a;
    Next();
    return;
}
}
else if (startcheck == false)
{
    if (calibrationcheck == false)
    {
        PlusButton.gameObject.SetActive(false);
        MinusButton.gameObject.SetActive(false);
    }
    RunCounter.gameObject.SetActive(false);
    StartButton.gameObject.SetActive(false);
    ar = false;
    Big();
    return;
}
}
else if (list == true)
{
    if (startcheck == true)
    {
        if (i == 1)
        {
            wheretomovecanvas.gameObject.SetActive(false);
            tomovecanvas.gameObject.SetActive(false);
            i = 0;
        }
    }
}
NextmoveButton.gameObject.SetActive(false);
    TimeButton.gameObject.SetActive(true);
}

```

```

ResetButton.gameObject.SetActive(true);
CancelInvoke();
startcheck = false;
Big_List();
return;
}
else if (i > 1)
{
a = i - 2;
i = a;
Next();
return;
}
}
else if (startcheck == false)
{
if (calibrationcheck == false)
{
PlusButton.gameObject.SetActive(false);
MinusButton.gameObject.SetActive(false);
}
RunCounter.gameObject.SetActive(false);
StartButton.gameObject.SetActive(false);
list = false;
Big();
return;
}
}
else if (ar == false && list == false)
{
BigBoard_list.gameObject.SetActive(false);
BigBoard_AR.gameObject.SetActive(false);
bigboard = false;
Test();
return;
}
}
else if (smallboard == true)
{
if (ar == true)
{
if (startcheck == true)
{
if (i == 1)

```

```

{
Destroy(GameObject.Find("pegtomoveprefab(Clone)"));
Destroy(GameObject.Find("placetomoveprefab(Clone)"));
Destroy(green_arrow);
Destroy(green_arrow2);
Destroy(red_arrow2);
i = 0;
NextmoveButton.gameObject.SetActive(false);
TimeButton.gameObject.SetActive(true);
ResetButton.gameObject.SetActive(true);
CancelInvoke();
startcheck = false;
Smallboard_AR();
return;
}
else if (i > 1)
{
a = i - 2;
i = a;
Next();
return;
}
}
else if (startcheck == false)
{
if (calibrationcheck == false)
{
PlusButton.gameObject.SetActive(false);
MinusButton.gameObject.SetActive(false);
}
RunCounter.gameObject.SetActive(false);
StartButton.gameObject.SetActive(false);
ar = false;
Small();
return;
}
}
if (list == true)
{
if (startcheck == true)
{

```



```

zeropointzerozero1.gameObject.SetActive(true);
X.gameObject.SetActive(true);
Y.gameObject.SetActive(true);
Z.gameObject.SetActive(true);
ExitCalibration.gameObject.SetActive(true);
CenterBoard.gameObject.SetActive(true);
LeftBoard.gameObject.SetActive(true);
RightBoard.gameObject.SetActive(true);
TopBoard.gameObject.SetActive(true);
Scale.gameObject.SetActive(true);
calibrationcheck = true;

double round = Math.Round(pegboard.transform.localScale.x,
4);

scaledisplay.x = (float)round;
round = Math.Round(pegboard.transform.localScale.y, 4);
scaledisplay.y = (float)round;
round = Math.Round(pegboard.transform.localScale.z, 4);
scaledisplay.z = (float)round;
string ScaleXString = scaledisplay.x.ToString();
string ScaleYString = scaledisplay.y.ToString();
string ScaleZString = scaledisplay.z.ToString();
ScaleX.text = ScaleXString;
ScaleY.text = ScaleYString;
ScaleZ.text = ScaleZString;
}

public void x()
{
    axis = "x";
    tweak.x = 0;
    tweak.y = 0;
    tweak.z = 0;
}
public void y()
{
    axis = "y";
    tweak.x = 0;
    tweak.y = 0;
    tweak.z = 0;
}
public void z()
{
    axis = "z";
    tweak.x = 0;
    tweak.y = 0;
    tweak.z = 0;
}

public void zero_point_1()
{
    if (axis == "x")
    {
        tweak.x = 0.1f;
        tweak.y = 0f;
        tweak.z = 0f;
    }
    if (axis == "y")
    {
        tweak.x = 0f;
        tweak.y = 0.1f;
        tweak.z = 0f;
    }
    if (axis == "z")
    {
        tweak.x = 0f;
        tweak.y = 0f;
        tweak.z = 0.1f;
    }
}

public void zero_point_zero_1()
{
    if (axis == "x")
    {
        tweak.x = 0.01f;
        tweak.y = 0f;
        tweak.z = 0f;
    }
    if (axis == "y")
    {
        tweak.x = 0f;
        tweak.y = 0.01f;
        tweak.z = 0f;
    }
    if (axis == "z")
    {

```

```

        tweak.x = 0f;
        tweak.y = 0f;
        tweak.z = 0.01f;
    }
}
public void zero_point_zero_zero_1()
{
    if (axis == "x")
    {
        tweak.x = 0.001f;
        tweak.y = 0f;
        tweak.z = 0f;
    }
    if (axis == "y")
    {
        tweak.x = 0f;
        tweak.y = 0.001f;
        tweak.z = 0f;
    }
    if (axis == "z")
    {
        tweak.x = 0f;
        tweak.y = 0f;
        tweak.z = 0.001f;
    }
}

public void exit_calibration()
{
    zeropoint1.gameObject.SetActive(false);
    zeropointzero1.gameObject.SetActive(false);
    zeropointzerozero1.gameObject.SetActive(false);
    X.gameObject.SetActive(false);
    Y.gameObject.SetActive(false);
    Z.gameObject.SetActive(false);
    Scale.gameObject.SetActive(false);
    if (bigboard == true && ar == true && startcheck == true)
        CursorVisual.gameObject.SetActive(false);

    axis = "";
    tweak.x = 0f;
    tweak.y = 0f;
    tweak.z = 0f;
}

```

```

    if (boardviewcheck == false)
    {
        CenterBoard.gameObject.SetActive(false);
        LeftBoard.gameObject.SetActive(false);
        RightBoard.gameObject.SetActive(false);
        TopBoard.gameObject.SetActive(false);
    }
    ExitCalibration.gameObject.SetActive(false);
    calibrationcheck = false;
    if (startcheck == true || (ar == false && list == false))
    {
        PlusButton.gameObject.SetActive(false);
        MinusButton.gameObject.SetActive(false);
    }
}

public void board_view()
{
    if (boardviewcheck == false)
    {
        boardviewcheck = true;
        CenterBoard.gameObject.SetActive(true);
        LeftBoard.gameObject.SetActive(true);
        RightBoard.gameObject.SetActive(true);
        TopBoard.gameObject.SetActive(true);
    }
    else if (boardviewcheck == true)
    {
        boardviewcheck = false;
        CenterBoard.gameObject.SetActive(false);
        LeftBoard.gameObject.SetActive(false);
        RightBoard.gameObject.SetActive(false);
        TopBoard.gameObject.SetActive(false);
    }
}

public void OnInputClicked(InputClickedEventData eventData)
{
    //handpos.x = 0f; handpos.y = 0f; handpos.z = 0f;
    //airtap = false;
}

```

```

        //airtap =
eventData.InputSource.TryGetPointerPosition(eventData.SourceId, out
handpos);
/*
(I made several attempts to differentiate between a remote
clicker "tap" and an airtap "tap".
They appear indistinguishable from a coding perspective,
which is annoying as I would have
liked to turn off the "airtap" gesture entirely, and only use
the clicker since it's
more reliable. Above, I tried to get the X,Y,Z position of
the user's hand at the time of
the airtap, logic being that if a position was returned (any
position), the click must have
come from the airtap. Unfortunately both the clicker and the
airtap both return a NULL
XYZ position, despite HoloLens documentation to the
contrary.)
*/

if (visiontestcheck == true) // && handpos.x == 0
{
    if (VisionTestCount == 1)
    {
        VisionTestTextGreen.text = "18436572";
VisionTestTextRed.text = "46164651";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = bottom;
temp.z = VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = top; temp.z = VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 2)
    {
        VisionTestTextGreen.text = "29527819";
VisionTestTextRed.text = "79834984";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = bottom;
temp.z = VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = top; temp.z = VisionTestTextRed.transform.localPosition.z;

```

```

        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 3)
    {
        VisionTestTextGreen.text = "16217912";
VisionTestTextRed.text = "89369525";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = top; temp.z =
VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = bottom; temp.z =
VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 4)
    {
        VisionTestTextGreen.text = "14570104";
VisionTestTextRed.text = "84656447";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = bottom;
temp.z = VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = top; temp.z = VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 5)
    {
        VisionTestTextGreen.text = "51649862";
VisionTestTextRed.text = "36478659";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = top; temp.z =
VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = bottom; temp.z =
VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 6)
    {
        VisionTestTextGreen.text = "79531648";
VisionTestTextRed.text = "61432684";

```

```

        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = top; temp.z =
VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
        temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = bottom; temp.z =
VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 7)
    {
        VisionTestTextGreen.text = "65963258";
VisionTestTextRed.text = "78606453";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = top; temp.z =
VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
        temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = bottom; temp.z =
VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 8)
    {
        VisionTestTextGreen.text = "48614695";
VisionTestTextRed.text = "82365574";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = bottom;
temp.z = VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
        temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = top; temp.z = VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 9)
    {
        VisionTestTextGreen.text = "96358746";
VisionTestTextRed.text = "06586459";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = top; temp.z =
VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;

```

```

        temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = bottom; temp.z =
VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 10)
    {
        VisionTestTextGreen.text = "96875642";
VisionTestTextRed.text = "53168432";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = bottom;
temp.z = VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
        temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = top; temp.z = VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 11)
    {
        VisionTestTextGreen.text = "36526978";
VisionTestTextRed.text = "46139652";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = bottom;
temp.z = VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
        temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = top; temp.z = VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 12)
    {
        VisionTestTextGreen.text = "65598765";
VisionTestTextRed.text = "24038312";
        temp.x =
VisionTestTextGreen.transform.localPosition.x; temp.y = top; temp.z =
VisionTestTextGreen.transform.localPosition.z;
        VisionTestTextGreen.transform.localPosition = temp;
        temp.x = VisionTestTextRed.transform.localPosition.x;
temp.y = bottom; temp.z =
VisionTestTextRed.transform.localPosition.z;
        VisionTestTextRed.transform.localPosition = temp;
    }
    if (VisionTestCount == 13)
    {

```

```

        visiontestcheck = false;
        VisionTestCanvas.gameObject.SetActive(false);
        VisionTest.gameObject.SetActive(false);
        Practice_button.gameObject.SetActive(true);
        Test_button.gameObject.SetActive(true);
        TimeButton.gameObject.SetActive(true);
        BoardView.gameObject.SetActive(true);
        ManualCalibration.gameObject.SetActive(true);
        VisionTestCount = 0;
    }
    VisionTestCount++;
}

if (startcheck == true) // && handpos.x == 0
{
    var obj = EventSystem.current.currentSelectedGameObject;
    if (obj.name != "NextButton" && obj.name != "Go Back" &&
obj.name != "ManualCalibration"
        && obj.name != "Plus" && obj.name != "Minus" && obj.name
!= "ExitCalibration"
        && obj.name != "0.1" && obj.name != "0.01" && obj.name
!= "0.001"
        && obj.name != "X" && obj.name != "Y" && obj.name != "Z"
&& obj.name != "Board View")
    {
        Next();
    }
}

void Timer()
{
    timecount = timecount + timelength;
}

public void Time_Button()
{
    if (timebuttoncheck == false)
    {
        timebuttoncheck = true;
        TimeSeries.gameObject.SetActive(true);
        ResetTimes.gameObject.SetActive(true);
        CurrentTime.gameObject.SetActive(true);
    }
}

```

```

    }
    else if (timebuttoncheck == true)
    {
        timebuttoncheck = false;
        resettimescheck = false;
        TimeSeries.gameObject.SetActive(false);
        ResetTimes.gameObject.SetActive(false);
        AreYouSure.gameObject.SetActive(false);
        CurrentTime.gameObject.SetActive(false);
    }
}

public void Reset_Times()
{
    if (resettimescheck == false)
    {
        AreYouSure.gameObject.SetActive(true);
        resettimescheck = true;
    }
    else if (resettimescheck == true)
    {
        AreYouSure.gameObject.SetActive(false);
        resettimescheck = false;
    }
}

public void Are_You_Sure()
{
    k = 0;
    TimeText1.text = "###.##"; TimeText2.text = "###.##";
    TimeText3.text = "###.##"; TimeText4.text = "###.##"; TimeText5.text
= "###.##";
    TimeText6.text = "###.##"; TimeText7.text = "###.##";
    TimeText8.text = "###.##"; TimeText9.text = "###.##"; TimeText10.text
= "###.##";
    TimeText11.text = "###.##"; TimeText12.text = "###.##";
    TimeText.text = "###.##";
    AreYouSure.gameObject.SetActive(false);
    resettimescheck = false;
}

void StartCheck()
{
    startcheck = true;
}

```

```
public void Vision_Test()
{
    if (visiontestcheck == false)
    {
        visiontestcheck = true;
        VisionTestCanvas.gameObject.SetActive(true);
        VisionTest.gameObject.SetActive(false);
        Practice_button.gameObject.SetActive(false);
        Test_button.gameObject.SetActive(false);
        TimeButton.gameObject.SetActive(false);
        BoardView.gameObject.SetActive(false);
        ManualCalibration.gameObject.SetActive(false);
    }
}
}
```

Protocol Number: NAWCAD.2019.0002-IR-EP4

Appendix D: IRB Protocol

**Naval Air Warfare Center Aircraft Division (NAWCAD)
Protocol for Human Subject Research**

Submission Date: 25 April 2019

Protocol/Research Title: Effects of Augmented Reality Based Object Illumination on Human Performance and Task Completion Time (Short Title: AR Based Object Illumination)

Protocol Number: NAWCAD.2019.0002-IR-EP4

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Joint/Cooperative Research:

N/A

Agreements/Contracts: (CRADA, Cooperative Research, etc.):

N/A

Funding Source:

Anticipated Start Date: June 1, 2019

Expected Duration of Research Effort: 3 Months

Version #: 1

Date: 25 April 2019

Protocol Number: NAWCAD.2019.0002-IR-EP4

Number of Subjects: 24

Identification of Medical Monitor:

Non-Technical/Lay Summary:

Extravehicular Activities (EVAs) in space are generally considered to be high-risk, costly activities, due to the nature of the working environment and the limitations imposed on astronaut mobility and dexterity. Specific procedures are scheduled out and rehearsed far in advance, with time being considered a precious commodity during missions. Providing artificial task guidance to astronauts could potentially improve their efficiency, enabling for shorter duration EVAs and/or a larger quantity of tasks completed.

This research aims to determine the effects of virtually illuminating objects of interest on a user's ability to complete a predefined task. This will be achieved through the use of a Microsoft HoloLens head mounted display. It is hypothesized that, by illuminating objects of interest, a user's eyes will be drawn to those objects faster, enabling the user to more quickly and accurately identify and interact with those objects. This could result in faster and/or more accurate completion of pre-defined tasks.

.....

Version #: 1

Date: 25 April 2019

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Approved for Public Release; Distribution is Unlimited

Protocol Number: NAWCAD.2019.0002-IR-EP4

Version #: 1

Date: 25 April 2019

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Approved for Public Release; Distribution is Unlimited

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II. Record of Changes to the Protocol

- Date: 25 April 2019 Initial Submission
- Date: Changes Subsequent to Scientific Peer Review
1.
- Date: Changes Subsequent to Safety Committee Review
1.
- Date: Changes Subsequent to Administrative Review
1.
- Date: Changes Subsequent to IRB Review
1.
- Date: Changes Subsequent to Continuing Review
1.

Version #: 1

Date: 25 April 2019

III. Scientific Background and Objectives

A. Background

“Hands-on” task time in space is generally considered to be a valuable commodity, especially during Extravehicular Activities (EVAs). Astronauts typically train for a year or more, before launching on a specific mission. Additionally, continuous ground support is required throughout the duration of each mission, and astronauts’ daily schedules are delineated into 2-minute blocks of time in order to maximize their task completion efficiency.

This becomes especially significant during EVAs, where the risks to safety are significantly higher. This is coupled with the fact that basic maneuverability, dexterous control and visibility are significantly reduced due to the nature of the spacesuit and the working environment.

It is proposed that implementing an Augmented Reality (AR) display into an astronaut’s spacesuit helmet could aid with object identification during an EVA activity, which could potentially allow the astronaut to complete individual EVA tasks more quickly and efficiently. This would help to reduce the abovementioned risks to safety, and increase the chances of mission success. Before any such technology is implemented into a real-world scenario, the effects of virtual illumination of real objects on user performance must be quantified. Here the term Virtual Illumination is defined as the technique of highlighting a specific real-world object of interest for the user, through the use of AR-based symbology/overlays which closely overlie the object from the user’s perspective.

B. Purpose/Objective

The objective of this effort is to determine the effect of AR based virtual illumination of real objects on a user’s ability to complete a predetermined set of tasks, both within and outside of the Head Mounted Display (HMD) field of view (FOV). This will be accomplished through the implementation of a modified Fitts’s Law Tapping Test, utilizing a Microsoft HoloLens HMD to provide both virtual illumination of real objects and a virtual checklist to serve as a control. Here the term Virtual Checklist is defined as the technique of directing the user’s attention to objects of interest via the use of written instructions, which are presented to the user via the HMD, and appear as a stationary “page” of written information. HMD FOV is defined as the angular span of the display as presented to the user (approx. 35 degrees horizontally by 17 degrees vertically).

Of particular interest is the HMD’s ability to draw a user’s attention to objects that are outside of its FOV, through the use of on-screen targeting symbology that directs the user’s attention toward the object of interest.

C. Hypothesis

- 1) Virtual illumination of real objects will draw a user’s attention to those objects faster
- 2) Faster object identification will allow for faster and more precise task execution.

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IV. Experimental Methods

A. Experimental Procedures and Rationale

1. Experimental Variables

Independent Variables:

- a. Virtual illumination vs. virtual checklist
- b. Task objects within HMD FOV vs. outside HMD FOV

Dependent Variables:

- a. Task completion time
- b. Peg movement accuracy

2. Environmental Conditions

Testing will occur on base at Naval Air Station (NAS) Patuxent River, Maryland, in a quiet room with minimal visual and auditory distractions. Subjects will be seated in a chair for the duration of the test.

3. Procedures and Rationale

Recruitment

Potential subjects for this effort will be military and/or civilian personnel located at NAS Patuxent River. Potential subjects will be recruited via flyers, email, and/or in-person (Appendices E, F). Potential subjects will be briefed on the study verbally and via the informed consent form.

Self-Identification

Potential subjects will be asked to self-identify whether they are pregnant at the time of the study. Pregnancy will not be a disqualifier for participation in the study, however pregnant women may be at an increased risk for experiencing nausea/motion sickness related symptoms as part of this study (see section V.B for further detail). Subjects will be specifically briefed on these risks as part of the overall study briefing.

Potential subjects will be asked to self-identify certain visual health information, including visual acuity, potential color-blindness, binocular vision (can they see with both eyes simultaneously), and if they've ever experienced photosensitive epileptic seizures (see Appendix B for the Visual Health History Questionnaire).

Vision Screening

Subjects will be screened for visual acuity, binocular vision, and color blindness through the implementation of a rudimentary vision screening. The screening will not quantify specific metrics such as visual acuity. Rather, it will simply determine whether the subject can distinguish symbology within the headset to a degree that is adequate for the study. Subjects will don the HMD. Multiple images and text will be displayed on each

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screen of the HMD (left and right), in various colors. The test conductor will ask the subjects to identify specific colors and text items on each screen. Subjects will need to identify the correct color and/or read the correct text each time, in order to pass the screening. Correct identification of each image and/or text item will be required, in order to demonstrate visual acuity, binocular vision and lack of color blindness. Visual acuity may be achieved via the use of corrective lenses.

Color blindness, lack of binocular vision, lack of adequate visual acuity, and a history of photosensitive epileptic seizures will all be disqualifiers for participation in this study (see section IV.B.3 for more detail). Potential subjects' above-mentioned personal medical information (PMI) will be documented and protected in accordance with standard practices for human subject research. Potential subjects who pass the screening process will be considered as subjects in the study.

Familiarization Training

Prior to testing, subjects will be familiarized with the HMD and the testing apparatus. Subjects will don the HMD, and will complete familiarization training which will consist of moving wooden pegs around on a vertical peg board. Subjects will take specific pegs from specific holes and place them elsewhere on the pegboard, according to a predetermined procedure. The procedure will be presented to the subjects in real-time, via either a virtual checklist or virtual illumination of the pegs and target holes. Subjects will train with both methods of information presentation, until their task completion times plateau for each method, prior to beginning the actual test.

Official Test

The official test will be similar to the familiarization training, in that subjects will be asked to move specific pegs around on a pegboard according to a predetermined procedure, which will be presented real-time in one of the two abovementioned display formats. The specific peg placement procedures for the test will be different from the familiarization training procedures. Subjects' task completion times and peg placement accuracy will be recorded. Each display format and each peg board size will have its own unique procedure, for a total of four test conditions. Each subject will complete all four test conditions in order to complete the test.

4. Test Conditions

The four test conditions are as follows: Virtual Illumination within the HMD FOV, Virtual Illumination outside the HMD FOV, Virtual Checklist within the HMD FOV, and Virtual Checklist outside the HMD FOV. Each test condition will produce two metrics, Completion Time and Peg Movement Accuracy (see section IV.A.1 Experimental Variables). The test conditions and metrics are laid out in the table below.

Display Method	Checklist		Holograms	
pegboard size	Small	Big	Small	Big

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test metric	Time	Accuracy	Time	Accuracy	Time	Accuracy	Time	Accuracy
-------------	------	----------	------	----------	------	----------	------	----------

5. Day-of-Test Procedure

- 1) The Test Subject arrives at the testing location and meets the Principal Investigator / Test Conductor. *(5 minutes)*
- 2) The Test Subject is verbally briefed on details of the test in general, as well as specific procedures for the session. *(5 minutes)*
- 3) The Test Subject is provided with the Informed Consent Form and Privacy Act Statement (Appendix A). *(5 minutes)*
- 4) Upon signing the Informed Consent Form, the Test Subject is provided with a Visual Health History Questionnaire to complete. (Appendix B and section IV.A.3 for further detail) *(5 minutes)*
- 5) Upon completing the Visual Health History Questionnaire, the Test Subject sits down at the test station. The Test Conductor adjusts the test station to adequately fit the Test Subject
 - i. Test Subject sits back in the chair with arms held up in front of them
 - ii. Test Conductor positions the pegboard such that the Test Subject’s arms reach the outer corners of the board.
 - iii. Test Subject confirms that they can adequately reach all areas of the board without leaving their seat
- 6) The Test Subject dons the HMD
- 7) The Test Subject undergoes vision screening through the use of the HMD *(10 minutes)*
 - i. Test Subject identifies the correctly colored display item with each eye
 - ii. Test Subject identifies the correct text item / image with each eye
- 8) The Test Subject Undergoes Familiarization Training (fam-runs) *(15x4 = 60 minutes total)*
 - i. The Test Subject completes practice runs in which they move pegs around on the pegboard. Each run consists of 10 movements. The Text Examiner records completion time and peg placement accuracy at the end of each run. *(< 1 minute each)*
 - ii. The Test Subject continues to complete practice runs until their completion time and peg accuracy plateau (see section IV.B.7 Data Analysis below for more detail)
 - iii. The Test Subject completes familiarization training for all four test conditions, in the order in which they are assigned to that particular subject (section IV.B.1 below for more detail) *(up to 15 minutes per test condition)*
- 9) Upon completion of familiarization training, the Test Subject removes the headset and takes a mandatory short break while the Test Conductor reconfigures the pegboard for the actual test. *(5 minutes)*
- 10) The Test Subject is re-seated and dons the HMD for the official test.
- 11) The Test Subject completes the official test *(20 minutes)*

- i. For each test condition, the Test Subject will complete three runs, consisting of 10 movements each (similar to familiarization training). The scores for the three runs are averaged to produce an overall score for each test condition.
 - ii. The Test Subject completes each test condition in their assigned order.
- 12) Upon completion of the official test, the Test Subject removes the HMD and exits the test station.
- 13) The Test Subject is provided with a post-study questionnaire (Appendix C), as well as a verbal de-brief of the study. (10 minutes)

B. Requirement for human volunteers and data analysis

1. Number Required

Based on four test conditions, there are 24 possible orders in which to complete the test. In order to reduce the effects of subjects becoming biased in favor of the first display method that they train on, all 24 orders will need to be evaluated. Therefore, 24 subjects will be required, with each one assigned to one particular test order.

2. Qualifications

Subjects will be military or civilian personnel over the age of 18. Physical requirements will be evaluated by the research conductors based on self-reported criteria as well as the abovementioned screening techniques (section IV.A.3 Vision Screening). Subjects must have a demonstrated binocular vision capability, with the ability to clearly distinguish between red, green, and blue displays. Visual acuity must meet or exceed that which is required for an unrestricted driver's license in the state of Maryland, 20/40 in each eye with a continuous field of vision of at least 140 degrees. This may be achieved via the use of corrective lenses.

3. Justification for Exclusion of Specific Groups

Visual Acuity:

Potential subjects whose vision does not meet the above qualifications will not be accepted for this study. The size of each individual peg and virtual display object (approx. ¼ inch at arm's length) will be comparable to the size of roadside signs and objects, when viewed at a reasonable distance from a vehicle on the road. Therefore, the state-mandated visual acuity requirements for an unrestricted driver's license will be adequate for the purposes of this study.

Binocular Vision:

Part of this study focuses on the effects of HMD FOV on task completion performance, specifically the fact that a typical user has wider peripheral vision, or FOV, than the HMD. Lack of binocular vision will restrict a subject's natural peripheral vision, which could potentially skew the data.

Color Blindness:

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During this study, multiple display colors will be used simultaneously to identify various objects of interest. Color blindness will negatively impact a subject's ability to correctly use virtual illumination to identify one object from another, which could skew the resulting data.

Photosensitive Epileptic Seizures:

Individuals who self-identify as having experienced photosensitive epileptic seizures will not be accepted for this study, as the study will require subjects to don and use a HMD which will display a series of video images for the subject to see.

4. Time Commitments of Subjects

- a) Study briefing – approx. 20 minutes
- b) Visual/medical history questionnaire and visual screening – approx. 10 minutes
- c) Introduction and familiarization training – approx. 30 minutes for each visual display method, or 1hour total
- d) Official test – approx. 30 minute

The entire time commitment for each subject should be no more than 2 hours, however, each subject's individual time commitment will vary slightly depending on their ability to successfully complete familiarization training.

5. Anticipated Testing Periods

Testing is anticipated to take place Sept. 1 – Sept. 30, 2019

6. Volunteer Recruitment

Potential subjects will be recruited via word of mouth, email, and flyers posted on base at NAS Patuxent River (see Appendices E, F).

7. Data Analysis

Familiarization Training

Test Subjects will complete practice runs until their completion time and peg accuracy plateau. Plateau is defined as a sequence of three runs (in order) in which the completion time and peg accuracy deltas for the SECOND and THIRD runs are less than 10% of the value of the FIRST run. For Example:

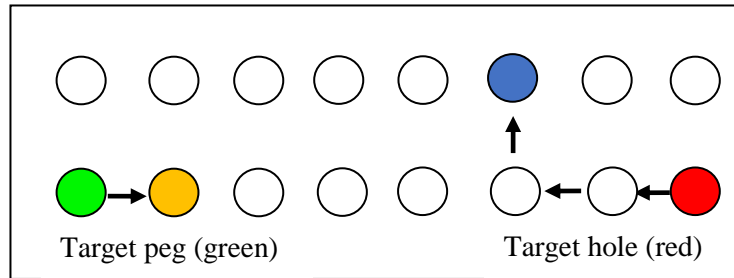
Run #	Completion time (seconds)	Delta	Plateau?
1	44		
2	34	10	
3	26	8	
4	23	3	
5	22	1	

6	21	1	PASS
---	----	---	------

This test subject's score plateaus after 6 runs, as the 5th and 6th run deltas are both less than 10% of the magnitude of the 4th run time.

Official Test

For the official test, test subjects will complete three runs for each test condition. Each run consists of 10 unique peg movements. Each run will produce a completion time score and a peg accuracy score. Completion time is measured as the length of time required for the test subject to complete one run, in seconds. Peg accuracy is measured as the number of holes away from the target hole that a test subject misses by, when attempting to place a peg. Similarly, if the test subject grabs the wrong peg to move, that distance will also be measured and included in the overall accuracy score. Peg accuracy is measured horizontally and vertically, but not diagonally. For example:



In the figure above, the test subject is supposed to take the peg from the green hole, however they mistakenly take a peg from the orange hole (+1). Similarly, they are supposed to place the peg in the red hole, however they mistakenly place it in the blue hole (+3). The arrows indicate how much the test subject missed by, for both the green hole and the red hole. Counting the arrows yields their total accuracy score for that particular move. In this case, their accuracy score would be 1 + 3 = 4, for that particular peg movement. A lower score indicates more accurate peg movement. A score of zero would indicate they moved the correct peg to the correct hole.

Accuracy scores for each movement will be summed to yield a total accuracy score for each run. Test subjects will complete three runs for each test condition, and the accuracy and time scores will be averaged to yield an overall accuracy score and time score for each test condition, for each test subject. This will produce 8 metrics, with 24 data points each. Within each metric, the data points are assumed to fit a normal distribution. A 95% confidence interval will be calculated for each metric, after which the confidence windows for each metric will be compared across display type and pegboard size, to look for observed trends in overall performance.

For example: Display method A produces a confidence interval of 28-33 seconds. Display method B produces a confidence interval of 39-45 seconds, for the same pegboard size. Both confidence intervals are 95%. One can say that, conservatively, display method A completion time is at least $39 - 33 = 6$ seconds faster than display method B, for that pegboard size. These comparisons will be made between display methods as well as pegboard sizes, for both data types, for a total of 8 comparisons.

Additionally, a Multi-Factor Analysis of Variance will be performed for each data type to determine any inter-relationships between pegboard size and display method.

C. Duties and Procedures to be Performed by Human Volunteers

1. Physiological Testing

All potential subjects will be screened for visual acuity, color blindness, and binocular vision via the use of a Microsoft HoloLens HMD (section IV.A.3 Vision Screening)

2. Physical Procedures

Subjects will don a Microsoft HoloLens HMD for the duration of subject screening, familiarization training, and testing (section IV.A.3). During familiarization training and testing, subjects will sit in a chair, and a vertical pegboard will be placed in front of them. The two pegboard sizes are roughly 2 feet square and roughly 3 by 4 feet, horizontally positioned. Subjects will be asked to maneuver specific pegs around to various locations on the pegboard, while their placement accuracy and completion times are measured. Subjects will be allowed to take breaks as required between individual runs. Images have been included below of the HMD, as well as its intended position on a user's head^{1,2}.



3. Subjective Measures

Subjects' self-reported comfort levels will be monitored throughout the study. Subjects will fill out a questionnaire at the conclusion of testing, which will ask which display technique they preferred and why, for each pegboard size (Appendix C).

4. Audio, Video or Digital Monitoring of Trials

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No audio or video monitoring of trials will take place. Subjects' abovementioned performance metrics will be recorded digitally, along with completed questionnaires and the research conductor's notes. This research data will be stored on the PI's government issue laptop computer. No personally identifiable information (PII) will be stored with the research data. PII will be maintained in a handwritten notebook, which will be locked in an approved, secure cabinet when not in use.

5. Termination Criteria

Testing will terminate for an individual subject / potential subject when all portions of the test have been completed, or at any time when one of the following occurs:

- i. If a potential subject fails to pass the initial visual screening process
- ii. If a subject or potential subject requests termination of their participation in the study, at any time, for any reason.
- iii. If a subject self-reports any signs of physical or mental discomfort at any point during the study, which they determine to be greater than minimal.
- iv. If the PI, medical personnel and/or research conductors notice a subject exhibiting any signs of physical or mental discomfort, which could be detrimental to the subject's health and/or the validity of the test data.

The PI, medical personnel, and research conductors may pause or terminate a subject's participation in the study at any time without the subject's consent, if they believe the action to be in the best interest of the subject. Additionally, a portion of the test may be paused or rescheduled in the event of equipment malfunction.

D. Required Equipment and Supplies

The study will use a Microsoft HoloLens HMD during all phases of testing. This device is battery powered, and will not be attached/plugged into a computer during screening, training, or testing phases, while a subject is wearing it.

Subjects will interact with two abovementioned pegboards during the training and testing phases of this study. The pegboards will be constructed specifically for this study, out of plywood, 2x4's and other readily available construction materials.

Task completion time will be recorded with a stopwatch or other time-keeping device with start/stop/pause functions.

V. Risks and Discomforts to Research Volunteers

A. Identification of Risks to the Volunteers and Means of Mitigation

The Microsoft HoloLens HMD, and AR in general, presents several known risks to user comfort³. These can include temporary feelings of nausea, motion sickness, dizziness, disorientation, headache, fatigue, eye strain, or dry eyes, and may be more prevalent for first-time users.

As quoted from the Microsoft HoloLens Health and Safety Information page³, these discomforts tend to be brought on/exacerbated by:

- “Being a new user - symptoms tend to decrease as your vision system adapts.
- Display not calibrated, or headset not oriented correctly on your head. Make sure HoloLens is properly calibrated and that it is properly aligned by using the Calibration application.
- Certain types of content, particularly games or movies that make you feel as if you are moving through space or looking down from high, or interactions that involve tracking moving objects.
- Using HoloLens for extended periods without a break.
- Using HoloLens in a completely dark environment that keeps you from seeing visual cues with your peripheral vision.”

These risks will be mitigated through the implementation of:

- A dedicated training/adjustment period prior to the test.
- Proper setup/calibration of the HMD at the beginning of every session, as part of screening or familiarization training.
- Static virtual symbology, which will be fixed in relation to the environment. The sole exception to this will be the targeting arrows and central cursor, which together act as a Heads Up Display (HUD) for the user, in a similar arrangement to current HUD technology in operational use with high performance jet aircraft today. The central cursor is static to the user’s FOV, and indicates where the user’s head is pointing. The targeting arrows are attached to the central cursor, and point in the direction of the peg of interest, in order to draw attention to it faster. They move in a predictable manner with respect to the user’s head, and they DO NOT move independently of the user’s head. Static symbology will include virtual circles and text boxes. Mobile symbology will include the targeting arrows and the central cursor.
- Periodic breaks as-required by the subject. The duration/number of breaks will vary by subject.
- An adequately lit test environment, with plenty of external visual cues.

Additionally, this study presents a potential risk of falling/tripping, if the subject is standing. This will be mitigated by requiring the subject to be seated while using the HMD. The pegboard will be positioned in such a way that every portion of it is within arm’s reach of the subject during a session, without requiring them to lean over excessively. The pegboard will be constructed and anchored in such a way that minimizes the risk of knocking it over during testing.

B. Special Risks to Pregnant or Potentially Pregnant Women

The abovementioned falling risk is more severe for pregnant women, but is again mitigated by requiring the subject to be seated during HMD operation.

Motion sickness and nausea related discomfort may be more severe for pregnant women. From the Microsoft HoloLens Health and Safety Information page³, “If you are prone to motion sickness in other situations, are afraid of heights, get migraine headaches, have an inner ear disorder, or other health conditions, you may be at increased risk of discomfort.” This risk will be mitigated as for other subjects, and will be continuously monitored throughout the study; however, the inherent risk of increased nausea will still be present for pregnant women.

C. Safety Precautions and Emergency Procedures

At any time during the study, a subject may stop participation for any reason by removing the HMD.

D. Assessment of Sufficiency of Plans to Deal with Adverse Events or Injuries

A medical monitor will be readily accessible during testing. Additionally, all subjects will have ready access to emergency medical facilities should an adverse event occur.

E. Qualifications of Medical Monitor and Medical Support Personnel

The medical monitor will be a physician or corpsman authorized to practice medicine by standards outlined by USN. Should a medical emergency occur, the subject will be transported to the nearest medical facility. Depending on the type and severity of an emergency, a subject will be taken to either the on-base clinic at NAS Patuxent River or a local hospital.

VI. Organization of Research Effort

A. Duties and Responsibilities of the Research Team

The principal investigator (PI), Matthew Stone (NAWCAD), will be responsible for experimental design of the study, obtaining and maintaining the data, coordinating data analysis, and adherence to IRB requirements.

B. Chain of Command

PI: Matthew Stone (4.6.7.1)
Branch Head: Robert Roy (4.6.7.1)
Division Head: Joseph Melotik (4.6.7)
Department Head: CDR Brent Olde, USN (4.6)

VII. Benefits

The data collected will add to the human performance body of knowledge, with regards to information presentation, and will help to guide future development of AR based displays for military and space applications. Efficient information presentation is critical to ensuring that maintainers can quickly and properly execute tasks. A more efficient maintainer community will

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directly benefit the warfighter's mission, by enabling quicker turnaround of equipment back to service.

In space, EVA activities are some of the riskiest endeavors for an astronaut. Enabling an astronaut to execute EVA tasks more efficiently will result in an increased value to those activities, while reducing the time required to remain on EVA. This will directly reduce the inherent risk to the astronaut.

VIII. Compensation

A chargeable object is available if required, in order to compensate for subjects' time participating in this study.

IX. Description of the System for Protecting Subject Privacy

A. Experimental Data

All experimental data will be stored in the NAVAIR 4.6 Auditory Performance Laboratory, BLDG 2187, 48110 Shaw Rd., Patuxent River, MD. Anonymity of subjects will be ensured by the use of coded data for all analyses and reporting. Data obtained in this study will be used for statistical analysis and reports by the Departments of the Navy and Defense, other U.S. Government agencies, and, when applicable, entities which contract with the U.S. Government, provided such use is compatible with the purpose for which the data were collected. Publication of data analyses may also be used for publication in open literature. Any publications reporting data from this study will assure anonymity of subjects, and will utilize data for evaluation purposes, to enhance basic medical knowledge, or to develop tests, procedures, and equipment to improve the diagnosis, treatment, or prevention of illness, injury, or performance impairment.

B. Research and Protocol, Consent Forms and Related Documents for Protection of Human Research Volunteers

All documents related to human research volunteers will be retained by the PI at NAWCAD, BLDG 2187, 48110 Shaw Rd, Patuxent River, MD.

C. Individual Medical Records

All medical records associated with participation in this study, including the Visual History Questionnaire, will be retained by the PI at NAWCAD, BLDG 2187, 48110 Shaw Rd, Patuxent River, MD.

IRB Protocol References

1. Wolverson, Troy; “Review: Microsoft's HoloLens offers glimpse of holographic future”, San Jose Mercury News, 6 Apr 2016, <https://phys.org/news/2016-04-microsoft-hololens-glimpse-holographic-future.html>
2. Moynihan, Tim; “Hands-On with Microsoft's HoloLens, One Year Later”, Wired, 17 Dec. 2015, <https://www.wired.com/2015/12/hands-on-with-hololens-groundbreaking-potential-for-ar/>
3. “Microsoft HoloLens Health and Safety Information”, Microsoft Corporation, <https://www.microsoft.com/en-us/hololens/legal/health-and-safety-information>

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INSTITUTIONAL OFFICIAL

- Approved
- Disapproved

Institutional Official (print) Signature Date