2022-09

SHIPBOARD 3-M PROGRAM SUPPLEMENTED BY AR TECHNOLOGY

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THESIS

SHIPBOARD 3-M PROGRAM SUPPLEMENTED BY AR TECHNOLOGY

by

Lowell J. Dixon

September 2022

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC, 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2022	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE SHIPBOARD 3-M PROGRAM SUPPLEMENTED BY AR TECHNOLOGY			**5. FUNDING NUMBERS**
6. AUTHOR(S) Lowell J. Dixon			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

The Navy maintenance program suffers from many inefficiencies, including poor labeling practices, difficult component identification, unspecific descriptions of component location in spaces for repair, and complicated diagrams. Maintenance programs onboard United States Naval Ships are a critical program to ensure they are prepared for combat and their duties by doing routine maintenance to equipment and keeping them in optimal working condition through repair. As mission difficulty and pace increases, these programs need to be carried out with fewer errors and more efficiently. Augmented reality (AR) technology can be used to identify and label all components in a space to assist with correctly identifying equipment and provide virtual instructions with critical, step-by-step information for conducting maintenance, inspections, repair work, and Damage Control (DC) events. Utilizing AR technology, Sailors or outside activity (i.e., contractors and shore-based repair facility Sailors) can enter a ship compartment and rapidly and accurately carry out a variety of maintenance program tasks. This technology would be particularly beneficial to inexperienced Sailors and outside activity by bolstering their limited knowledge and assisting them in the identification and prioritization of critical tasks and items, while simultaneously reducing the time required, and number of errors committed, while performing those tasks.

14. SUBJECT TERMS AR, augmented reality, maintenance, technology, shipboard, maintainer			**15. NUMBER OF PAGES** 79
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

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SHIPBOARD 3-M PROGRAM SUPPLEMENTED BY AR TECHNOLOGY

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
September 2022

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ABSTRACT

The Navy maintenance program suffers from many inefficiencies, including poor labeling practices, difficult component identification, unspecific descriptions of component location in spaces for repair, and complicated diagrams. Maintenance programs onboard United States Naval Ships are a critical program to ensure they are prepared for combat and their duties by doing routine maintenance to equipment and keeping them in optimal working condition through repair. As mission difficulty and pace increases, these programs need to be carried out with fewer errors and more efficiently. Augmented reality (AR) technology can be used to identify and label all components in a space to assist with correctly identifying equipment and provide virtual instructions with critical, step-by-step information for conducting maintenance, inspections, repair work, and Damage Control (DC) events. Utilizing AR technology, Sailors or outside activity (i.e., contractors and shore-based repair facility Sailors) can enter a ship compartment and rapidly and accurately carry out a variety of maintenance program tasks. This technology would be particularly beneficial to inexperienced Sailors and outside activity by bolstering their limited knowledge and assisting them in the identification and prioritization of critical tasks and items, while simultaneously reducing the time required, and number of errors committed, while performing those tasks.

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
AFRL	Air Force Research Laboratory
AR	augmented reality
ARMAR	Augmented reality for Maintenance and Repair
BAE	British Aerospace
CNO	Chief of Naval Operations
CSMP	Current Ship's Maintenance Project
DNF	did not finish
EDSRA	Extended Docking Selected Restricted Availability
EQV	Equipment Validation
GAO	Government Accountability Office
GE	General Electric
HMD	helmet-mounted display
HUD	head-up display
HWD	head-worn display
ID	Identification
IMA	intermediate maintenance activity
MOVES	Modeling Virtual Environments and Simulation
NAVSEA	Naval Sea Systems Command
NPS	Naval Postgraduate School
RMC	Regional Maintenance Center
SDTS	Self Defense Test Ship
SWO	Surface Warfare Officer
TYCOM	Type Commander
USFF	U.S. Fleet Forces Command
VR	virtual reality

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EXECUTIVE SUMMARY

United States Navy surface ship maintenance has become a billion-dollar industry that plays a significant part in the readiness, capacity, and capability of the U.S. Navy surface fleet. The U.S. Navy's newly proposed 435-ship fleet will require approximately $159.9 billion over the next 10 years to procure, man, and maintain (O'Rourke, 2020). The efficiency of the maintenance and repair of surface ships is critical due to its impact on readiness and the sheer cost. Unfortunately, the maintenance and repair of the surface fleet experiences schedule delays from various sources that result in increased cost and less availability for fleet missions. This thesis focuses on "new work" (i.e., work to equipment without scheduled maintenance that is added after initial contract completion for maintenance availability) and "growth work" (i.e., work to equipment with scheduled maintenance that is added after initial contract completion for maintenance availability) (Office of the U.S. Fleet Forces Command [USFF], 2022, p. II-I-3-50).

Both, "new work" and "growth work" are caused, in part, by an inability to identify maintenance items in a timely manner and misidentifying items (e.g., in cases where many similar objects are in a single space). An example of this is USS Tortuga (LSD 46), which entered an Extended Docking Selected Restricted Availability (EDSRA) scheduled from January 2018 to May 2019 at British Aerospace (BAE) Systems Norfolk Ship Repair for "$139.8 million to repair and modernize" the ship (LaPorta, 2017). USS Tortuga has suffered several delays resulting in an extension of the EDSRA to fall of 2023 and increase of over $210 million, which means approximately a 300% increase in time and money to complete (K. Lasua, personal communication, July 27, 2022).

A potential solution that can mitigate these cost and schedule overruns is Augmented Reality (AR) technology. According to Wang and colleagues (2020), AR is the ability "to combine virtual elements into real scenes, mixing real scenes with virtual scenes, and the information in the two views superimposed and strengthened each other," which allows people's awareness and capacity to process information to be enhanced. The ability to cue real-time information like technical manuals, instructions, or visual directions can save time and reduce errors for maintainers locating objects.

AR has demonstrated benefits in performing maintenance in various military branches. Henderson and Feiner (2007), working with the Air Force Research Laboratory (AFRL), illustrated AR's ability to not only reduce workload, as measured by reduced head and eye movement, but also reduced time for transitioning repair sequences and enabling effective real-time collaboration. Thus, as a solution for maintenance tasks that depend on accurately and quickly locating items, AR is a highly promising solution for the surface fleet.

This thesis will expand on a previous NPS thesis, AR Technology Effect on Efficiency of Shipboard Maintenance (Wiltshire, 2021), which focused on (I) determining attitudes among the surface warfare community towards implementation of shipboard AR technology, and (II) conducted limited experimentation comparing search behavior with and without AR technology in a laboratory environment. Crucially, Wiltshire (2021) was not able to test the AR technology on an actual ship, or with the intended user population.

This thesis used the same experimental method and equipment, but was able to collect data on a real U.S. Navy ship with actual sailors and contractors that conduct shipboard maintenance. The first independent variable was the availability of AR technology. This was the between-subjects condition, with two levels: no AR headset (control group) and AR headset (experimental group). The second independent variable was the complexity of the environment which participants were searching. This was the within-subjects condition, with two levels: Simple Environment (represented by the Wardroom) and Complex Environment (represented by Shaft Alley and Sewage Plant Room #2). The dependent variables for all groups were time, measured in seconds, and accuracy, measured by counting the number of items the participants correctly identified.

We recruited 10 participants and split them evenly between the AR group and the Control group. Each participant had to find 10 items in the Simple space followed by 10 items in the Complex space. The AR group used virtual aids in the form of Heads-Up symbology and directions projected through the Microsoft HoloLens 2. In contrast, the Control group received a packet of paper with each item in order a detailed description of how to find the item, that was similar to, but more detailed than, the typical work candidates that outside activity would use to locate a maintenance item.

The results demonstrate that AR technology significantly increased accuracy compared to the current process (i.e., reading written instructions), as all participants in the AR group found 100% of the maintenance items, regardless of the complexity of the search space. AR technology additionally allowed participants to spend significantly less time identifying maintenance items compared to the current process. The time savings realized by AR technology over the current process was significantly greater in the Complex space compared to the Simple space. During actual maintenance availabilities, these time savings afforded by AR technology would translate to cost savings through a reduction in outside activity (i.e., contractors that charge their time) failing to identify or locate maintenance items within a reasonable time, and those items later being tacked on as "new" or "growth" work. As such, implementing AR technology would eliminate a significant cause of delays in maintenance availabilities.

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ACKNOWLEDGMENTS

I would like to give a special thanks to Dr. Aditya Prasad for his dedicated efforts as my advisor. Dr. Prasad has been extremely helpful throughout my research and the writing of my thesis. I would also like to give a special thanks to Clay Greunke who was not only my second reader, but the subject-matter expert throughout my research. Their support has gotten me to this point.

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I. INTRODUCTION

A. RESEARCH PROBLEM AND MOTIVATION

United States Navy surface ship maintenance has become a billion-dollar industry that plays a significant part in the readiness, capacity, and capability of the U.S. Navy surface fleet. The U.S. Navy's previously proposed 355-ship fleet would have required an additional $130 billion over the next 10 years to procure, man, and maintain the fleet, while the newly proposed 435-ship fleet will require approximately $159.9 billion over the next 10 years compared to the current budget (O'Rourke, 2020). According to Edwards (2021), the U.S. Navy has awarded $1.74 billion for the maintenance and repair of ships to San Diego shipyards. The efficiency of the maintenance and repair of a ship is critical due to its impact on readiness and the sheer cost. Unfortunately, the maintenance and repair of the surface fleet commonly experiences schedule delays from a variety of sources that result in increased cost and less availability for fleet missions. An example of this is USS Tortuga (LSD 46), which entered an Extended Docking Selected Restricted Availability (EDSRA) scheduled from January 2018 to May 2019 at British Aerospace (BAE) Systems Norfolk Ship Repair for "$139.8 million to repair and modernize" the ship (LaPorta, 2017). USS Tortuga has suffered several delays, resulting in an extension of the EDSRA to the Fall of 2023 and a cost increase of over $210 million, resulting in an approximately 300% increase in time and money to complete (K. Lasua, personal communication, July 27, 2022).

The contributing factors for these delays that this thesis focuses on is the improper or untimely identification of maintenance items. Every level of maintenance suffers from these problems, whether it be outside activity (i.e., contracted civilians and Navy personnel from repair centers) during an intensive maintenance availability or when the ship's crew are repairing the ship. The current process for recording maintenance discrepancies is a digital list called the Current Ship's Maintenance Project (CSMP). Maintenance discrepancies are recorded as "work candidates" that require a description of the item location by the sailor. The only method for the outside activity to locate and identify these discrepancies is by using the work candidate. This process is subject to human error, variability, and a lack of clarity, all of which often lead to increased time and cost to the overall maintenance process. According to the OPNAVINST 4700.7M, to schedule or execute maintenance there must be objective evidence to justify it (Office of the Chief of Naval Operations [CNO], 2019). As such, if the outside activity cannot properly identify maintenance items, then the repair will not be completed, thereby resulting in degraded readiness.

Augmented reality (AR) is a technological solution used for maintenance tasks and localization of items in industry, and is the most promising solution for locating maintenance items onboard surface ships. For example, AR has been used to assist the Boeing Company in improving productivity by 40% ("Boeing: Boeing Tests Augmented Reality in the Factory," 2018). The Boeing technicians accomplished this by enabling them to view 3D wiring diagrams through an AR head-worn display (HWD) instead of the viewing the time-intensive traditional 2D wiring diagrams that could span 20 feet in length.

This example demonstrates how AR can be used to save time and increase accuracy in search-intensive maintenance tasks. AR gives users the ability to see their normal environment with overlayed digital information to augment their sense of sight and provide attentional and cognitive support in high-workload tasks. Examples of these digital overlays include text, directional arrows, bounding boxes that highlight items, displaying alternate levels of a view, walkthrough procedures with animations, and other creative enhancements. These enhancements could make locating maintenance items faster and more accurate, thus saving the Navy money and reducing maintenance availability delays.

B. SCOPE OF THESIS

This thesis will expand on the research conducted in *AR Technology Effect on Efficiency of Shipboard Maintenance* (Wiltshire, 2021). Wiltshire's (2021) effort focused on determining attitudes among the surface warfare community towards adopting shipboard AR technology and included limited experimentation comparing search behavior with and without AR technology in a laboratory environment. Crucially, this previous effort was not able to test AR technology on an actual surface ship or with the intended user population (i.e., outside activity or ship's company). This thesis will expand on those results by utilizing the AR test methodology developed by Wiltshire (2021) and conducting more representative research, involving active-duty U.S. Navy sailors assigned to the Self Defense Test Ship (SDTS), in actual shipboard spaces. The SDTS is a modified ship formerly known as USS Paul F. Foster (DD 964), is a remote-controlled ship and used as a test ship for various technologies and systems.

C. RESEARCH QUESTIONS

This thesis will address the following research questions:

1. Does the use of augmented reality to identify maintenance items increase efficiency, both in terms of time and accuracy, compared to the current process?
2. Does the use of augmented reality to identify maintenance items improve the accuracy and time of identification to a similar extent in both Simple and Complex shipboard spaces?

D. HYPOTHESES

Our first hypothesis will investigate whether the use of AR technology improves the accuracy with which maintenance items are located. As in previous research (see Wiltshire, 2021), we predict that the use of AR technology, which provides a visual overlay of the real world augmented with icons directing users to the appropriate item, will reduce both the frequency of misidentified items and cases in which the item simply isn't found in a timely manner (defined here as a 180-second time limit per item).

1. Accuracy

Null Hypothesis ($H1_0$): The control group and the AR group will exhibit no difference in mean accuracy in identifying maintenance items, $\mu_{control} - \mu_{AR} = 0$.

Alternative Hypothesis ($H1_A$): the control group has a lower mean accuracy in identifying maintenance items than the AR group, $\mu_{control} - \mu_{AR} < 0$.

2. Time

Time is the second of the two major factors contributing to schedule delays in maintenance availabilities that this thesis will investigate. As in previous research (see Wiltshire, 2021), we predict that AR technology will allow users to more quickly identify maintenance items than those who have to rely upon the current method, which involves reading written instructions.

Null Hypothesis ($H2_0$): There is no difference in the mean time to identify maintenance items between the control group and the AR group, $\mu_{control} - \mu_{AR} = 0$.

Alternative Hypothesis ($H2_A$): On average, the control group takes longer to identify maintenance items compared to the AR group, $\mu_{control} - \mu_{AR} > 0$.

3. Search Space Complexity

Hypothesis 3 & 4 evaluate the benefits of AR technology on time and accuracy in search spaces of differing complexity. These hypotheses are an extension of a trend observed in prior research (see Wiltshire, 2021). Hypotheses 1 & 2 predict that users who have access to AR technology will, overall, be more accurate and take less time than users who must rely on the current method (reading written instructions). Hypotheses 3 & 4 further predict that there will be no significant difference in the mean time or accuracy of users who use AR regardless of whether they are searching for maintenance items in a Simple space or a Complex space. In contrast, those who use the current method will exhibit significantly worse mean accuracy and time when searching for maintenance items in the Complex space versus the Simple space.

Null Hypothesis ($H3_0$): There is no delta in the Control group's mean time when identifying maintenance items in a Simple ship space compared to a Complex ship space, $\mu_{simple} - \mu_{complex} = 0$.

Alternative Hypothesis ($H3_A$): The Control group is significantly slower when searching for maintenance items in the Complex ship space compared to the Simple ship space, $\mu_{complex} - \mu_{simple} > 0$.

Null Hypothesis ($H4_0$): There is no difference in the Control group's mean accuracy when identifying maintenance items in the Simple ship space compared to the Complex ship space, $\mu_{simple} - \mu_{complex} = 0$.

Alternative Hypothesis ($H4_A$): The Control group commits significantly more errors when searching for maintenance items in the Complex ship space compared to the Simple ship space, $\mu_{complex} - \mu_{simple} > 0$.

E. BENEFITS OF STUDY

The current maintenance process has inefficiencies that lead to significant schedule delays and increased costs in maintenance availabilities. The primary benefit of this research is the demonstration of real-world decreases in completion time and increases in accuracy that AR technology can make in maintenance tasks, thereby resulting in the potential to save the U.S. Navy millions of dollars compared to the current maintenance process. The current maintenance process is incapable of supporting a future naval force of 435 ships in operational readiness as proposed in the 2020 Integrated Naval Force Structure Assessment (O'Rourke, 2020). In prior research (Wiltshire, 2021), AR experiments were conducted in a classroom setting, utilizing Naval Officers of varying backgrounds (i.e., non-maintenance) looking for items in a classroom (the Simple space) and a laboratory (the Complex space). Conducting this experiment on a real U.S. Navy ship with real maintenance items provides critical insights in a pseudo-operational environment that could not be represented in an NPS classroom and laboratory. In addition, this research provides the ability to measure sailor performance, institute training programs for orienting sailors to spaces and equipment, and optimize a variety of maintenance practices on Navy vessels in realistic operating conditions.

F. THESIS STRUCTURE

Chapter I covers the introduction of the research problem, its motivation, and proposed research questions and hypotheses to test.

Chapter II covers the background information for AR and its capabilities, current maintenance processes, and maintenance delays.

Chapter III covers the methodology for the experiment, the demographic survey, and the post-task survey.

Chapter IV covers the analysis of the experiment results.

Chapter V covers the discussion of the results, conclusions, limitations of the study, results implications, and future research.

II. BACKGROUND

A. CURRENT SHIPBOARD MAINTENANCE PROCESS (CSMP)

According to the Office of the CNO (2019, 1–2), "Navy ship maintenance policies and actions are designed to ensure crew and ship safety while achieving desired operational readiness levels within current system capabilities, at the lowest possible total ownership cost, consistent with public law and other directives." The CSMP holds all the maintenance items awaiting repair, for any maintenance level, in electronic form for the ship (Office of the Naval Sea Systems Command [NAVSEA], 2021). The maintenance repairs in the CSMP are called work candidates. According to COMUSFLTFORCOMINST 4790.3 REV D CHG 2 (Office of the U.S. Fleet Forces Command [USFF], 2022), a valid work candidate must contain the following: configuration information to include the location and equipment identification information, job sequence number, equipment status code, discovery date, deferred date, symptoms and supporting information, first contact name, priority, type availability, required delivery date, recommended resolution, maintenance action requested, maintenance figure of merit in CSMP shore file, initial estimate in CSMP Shore file, Type Commander (TYCOM) screening code, and the TYCOM screening remarks in CSMP shore file. The ship's force is tasked with keeping the CSMP updated and accurate to facilitate tracking of all current issues on the ship.

During extensive maintenance periods, maintenance and repairs conducted by outside activity rely on the location details written in the work candidate to find the maintenance item in need of repair. It is difficult and time consuming to find maintenance items due to the limited ability to describe in words the exact location and appearance of many items, especially in complex spaces or where multiple similar items exist. An example from a CSMP would be identifying the space as Well Deck (1-131-0-Q) and saying that the third lightbulb case is missing one screw. In this example, the space is identified, but for outside activity to determine what method the originator of the work candidate used to describe the lightbulb case's location (i.e., *third* lightbulb case) is a mystery, as it could be third case from any of the walls in the space. To illustrate this, the Well Deck has well over 100 lightbulbs and requires a rented aerial work platform to get close enough to observe if a light bulb case is missing a screw. This is just one example of just how much time and money can be spent just identifying the maintenance item.

1. Levels of Shipboard Maintenance

Organizational Level Maintenance is conducted by the ship's force (NAVSEA, 2021, p. C-7). Ship's force consists of those personnel that typically oversee equipment operation and are assigned to the ship.

Intermediate Level Maintenance is "normally accomplished by centralized repair facility personnel such as a Navy fleet maintenance activities, submarine refit and support facilities, Regional Maintenance Centers (RMCs), and battle group or other intermediate maintenance activities" (NAVSEA, 2021, p. C-5). These personnel typically provide above what ship's force can accomplish skill-wise, capability-wise, or capacity-wise.

Depot Level Maintenance "consists of maintenance tasks that focus on repair, fabrication, manufacture, assembly, overhaul, modification, refurbishment, rebuilding, test, analysis, design, upgrade, painting, assemblies, subassemblies, software, components, or end items that require specialized facilities, tooling, support equipment, personnel with higher technical skill, or processes beyond the scope of the intermediate maintenance activity (IMA)" (NAVSEA, 2021, p. C-2)

2. Current Shipboard Maintenance Method

The outside activity is limited to the location and identifying information written in the work candidate, so if it is insufficient or a contractor is unfamiliar with this system, then maintenance items can be left unscheduled. These items can then be caught at a later time, creating "new work" (i.e., work to equipment without scheduled maintenance that is added after the initial contract for the maintenance availability is completed) or "growth work" (i.e., work to equipment with scheduled maintenance that is added after the initial contract for a maintenance availability is completed) (USFF, 2022, p. II-I-3-50). Due to these additional contracting requirements, any growth work or new work adds significant additional cost and time to complete the maintenance, thus impacting the ship's operational cycle. With AR technology, the outside activity could locate these maintenance items more easily, even in Complex ship spaces, as the item would be highlighted and directional cues would be given to assist in the location. A Government Accountability Office (GAO) report found that 75% of aircraft carrier and submarine maintenance periods between 2015 and 2019 were late, by an average of four months for aircraft carriers and seven months for submarines, in part due to work identified after maintenance plans were finalized (Maurer, 2020).

Organizational Level Maintenance that is conducted by the ship's force requires many man-hours of time and often brings equipment and systems down during the scheduled maintenance. When taking into account the sheer number of maintenance tasks that are needed to be completed daily by the entire ship, the use of AR could save hundreds of man-hours a week. AR technology can be used to quickly identify maintenance items and even have the maintenance procedures loaded into virtual text and visual cues to assist sailors. Equipment validations are required of all equipment aboard the ship every 36 months and are conducted by ship's force as another component of the maintenance program (USFF, 2022, p. VI-19-6-49). With thousands of pieces of equipment on each ship, it becomes a time-consuming action to verify them even within 36 months and they are often hard to find due to: (1) a limited ability with just the compartment space listed for where to find the equipment, and (2) the complexity of the space. Typically, it takes several hours to verify all the equipment within a space. With AR, a sailor could quickly find each piece of equipment in a space that needed to be verified. The Equipment Validation (EQV) list could be loaded into the AR device's software, selected, and then it would walk the sailor through the location of each item by highlighting it and giving directional cues.

3. Previous Research

Prior research on this topic focused exclusively on Intermediate Level Maintenance and Depot Level Maintenance, which are the only levels that require outside activities to complete (Wiltshire, 2021). At the Intermediate and Depot Level, it was determined that Surface Warfare Officer's (SWO's) would be receptive to AR technology to aid in bridging the gap between ship's force and outside activities. Further, use of AR technology improved user confidence in identifying maintenance items and AR technology could improve efficiency of identifying maintenance items, both in terms of timeliness and accuracy. Given these findings, this thesis seeks to further demonstrate the benefits of AR technology in improving accuracy and timeliness, thus saving costs, caused by poorly or improperly documented work candidates in Organizational Level Maintenance to be conducted by ship's force.

B. AUGMENTED REALITY

According to Wang and colleagues (2020), AR is the ability "to combine virtual elements into real scenes, mixing real scenes with virtual scenes, and the information in the two views superimposed and strengthened each other," which allows people's awareness and capacity to process information to be enhanced.

There are six different types of AR: projection-based AR, marker-based AR, location-based AR, outlining AR, markerless AR and superimposition AR. Doegar (2021) states that projection-based AR is the projection of virtual images onto physical objects in the physical space and may or may not be interactive. Marker-based AR uses the detection and recognition of AR markers to generate corresponding objects or translates words detected with camera. According to Doegar (2021), location-based AR uses digital content that "is mapped to a specific location," which allows users to see digital content when they enter the preprogrammed area. Outlining AR utilizes object recognition to create outlines. Markerless AR does not use markers and scans environment, which allows user to insert digital content without moving anything in the background. Superimposition AR replaces part or all of an object with an augmented image via object recognition.

Several hardware types utilize AR. There are smartphones and tablets that have downloadable AR applications. Some smart glasses come with built-in AR technology like the Google Glass (Kloberdanz, 2017). There exist some kiosks and similar installations that utilize AR. The heads-up display (HUD) consists of "3 main components: a projector unit, a viewing glass (combiner, and a computer (symbol generator)" ("4 Types of Augmented Reality Devices That You Must Know," 2021). When the HUD is integrated with a helmet, it is called a helmet-mounted display (HMD). A holographic display "uses light diffraction to display 3D objects in the form of a still image or animated sequences in real life" ("4 Types of Augmented Reality Devices That You Must Know," 2021).

1. AR in Military Maintenance

AR has been experimented with over the years to test the effect it can have on performing maintenance in various military branches. A study by Henderson and Feiner (2009) used an AR HWD where maintenance tasks of a Marine armored personnel carrier turret where it was found that it "allowed mechanics to locate tasks more quickly than when using either baseline, and in some instances, resulted in less overall head movement" (pg. 135). The HWD tracked the user in the space and gave directional hints for shortest distance to the next maintenance task and highlighted it once looking at it. The HWD also offered some 3D instructions for the task.

AR has multiple features that make it an ideal tool to aid maintainers executing complex tasks where errors cannot be tolerated. The U.S. Air Force Research Laboratory (AFRL), in conjunction with Columbia University (Henderson & Feiner, 2007), demonstrated that an AR solution called Augmented reality for Maintenance and Repair (ARMAR) not only reduced workload, as measured by reduced head and eye movement, but also reduced the time for transitioning repair sequences, enabled effective real-time collaboration, and presented step-by-step instructions with contextual warnings to the user. ARMAR proved its capabilities in a test where the user utilized an AR HWD to walk through a step-by-step virtual instruction on removing a Dart 510 oil pressure transducer. An untrained maintainer could use these instructions to complete the otherwise complex procedure and even included warnings to prevent injury to the user or equipment.

2. AR in Industry Maintenance

One of the biggest issues facing industry is "human error which may cause a loss of millions of dollars" ("Augmented Reality in Aviation Industry," 2021). AR technology can be used to "inspect, maintain and repair aircraft" through immersive technology, ability to que real-time information, and contact experts within AR space (Augmented Reality in Aviation Industry, 2021). The ability to cue real-time information like technical manuals or instructions can save time while the ability to have an expert see the same thing as users and guide the user through the maintenance procedure can save time and reduce errors. No longer would you need to fly out experts saving money and time as the less experienced person would be able to do the maintenance with live assistance.

Masoni and colleagues (2017) stated that to reduce the time to complete maintenance tasks and errors, AR can be used in a real working environment for job task training and guidance for novice technicians. They developed a remote maintenance AR system that fed one or more unskilled operators' screenshots of equipment to a maintenance expert who could communicate with the operator to indicate certain maintenance tasks through universal language symbology, text messages, and elaborating sketches that appeared in their AR display or tablet.

The Upskill Company in conjunction with General Electric (GE) Ventures and GE Aviation built an AR solution through use of Glass (formerly Google Glass) and a smart torque wrench (Kloberdanz, 2017). The Glass is a pair of glasses with AR projected onto the lens. The Upskill software called Skylight alerts mechanics when a torque wrench is required to tighten nuts while building a jet engine. It works by having the mechanic use a wifi-enabled torque wrench that in real-time when it applies "torque, it shares the information with the Skylight server. Skylight then tells the mechanic whether they are properly tightening and sealing crucial jet engine b-nuts" (Kloberdanz, 2017). Without this the mechanics would have to refer to manuals or call experts to confirm the correct torque value, but with the AR system they can bring up digital directions, videos with training, or utilize voice to call experts. When contacting experts, they can stream their view to the expert and receive a walkthrough. Kloberdanz (2017) conducted an experiment with 15 mechanics that found "the efficiency improvements were between 8 and 11 percent, a number that might grow once the learning curve for use of the devices is mastered."

3. Previous AR Study

Prior thesis work by Wiltshire (2021) utilized a Microsoft HoloLens 2 AR headset along with software designed by the Naval Postgraduate School (NPS) Future Tech Team. These tools were used to create and view persistent, custom-sized virtual tags of items in NPS classrooms or laboratory spaces. The Experimental group utilized AR to find a list of items inside the classroom ("Simple space") or laboratory ("Complex space"), while the Control group used the current process of reading a location description similar to what is found on a work candidate shown in Figure 1 and the location description featured in Figure 2. The AR group got an introductory period to get acquainted with using it before conducting a trial run while the Control group would get an explanation before their trial run. The experiment had each participant identify 10 items in the classroom and 12 items in the laboratory. Participants had to identify the items in the order they were listed. Once they had identified the item, or believed they had, they would call out the Component Identification (ID) Number, state their confidence level, and continue working down the list until complete with all items in both spaces (Wiltshire, 2021). The Experimental group was 81.6% faster in the Simple space and 103.2% faster in the Complex space, while their accuracy was 100.0% for both spaces and their confidence level in identifying the maintenance items was 93.4%. In contrast, the Control group had a 93.6% accuracy overall, and their confidence was only 85.6%. Wiltshire (2021) stated that potential future research could include increasing the size and representativeness of the sample, identifying compounding negative effects from the incorrect identification of maintenance items, determining a threshold for AR's efficacy increases, determining if a relationship exists between the maintenance item and a participant's confidence level, creating a cost simulation to determine the cost benefit of using AR technology, and collecting data in an operational environment (e.g., an actual Navy ship).

This thesis explored the last of these recommendations by utilizing the same methods but collecting data on the SDTS. There were 10 participants total, five in the AR group and five in the Control group, consisting of volunteers from the SDTS command. The AR group got a brief, one-minute introduction instead of a 20-minute training session. This thesis also investigated whether there was a significant difference in the benefits AR technology provided, in terms of time and accuracy, when searching for maintenance items in a Simple space and a Complex space.

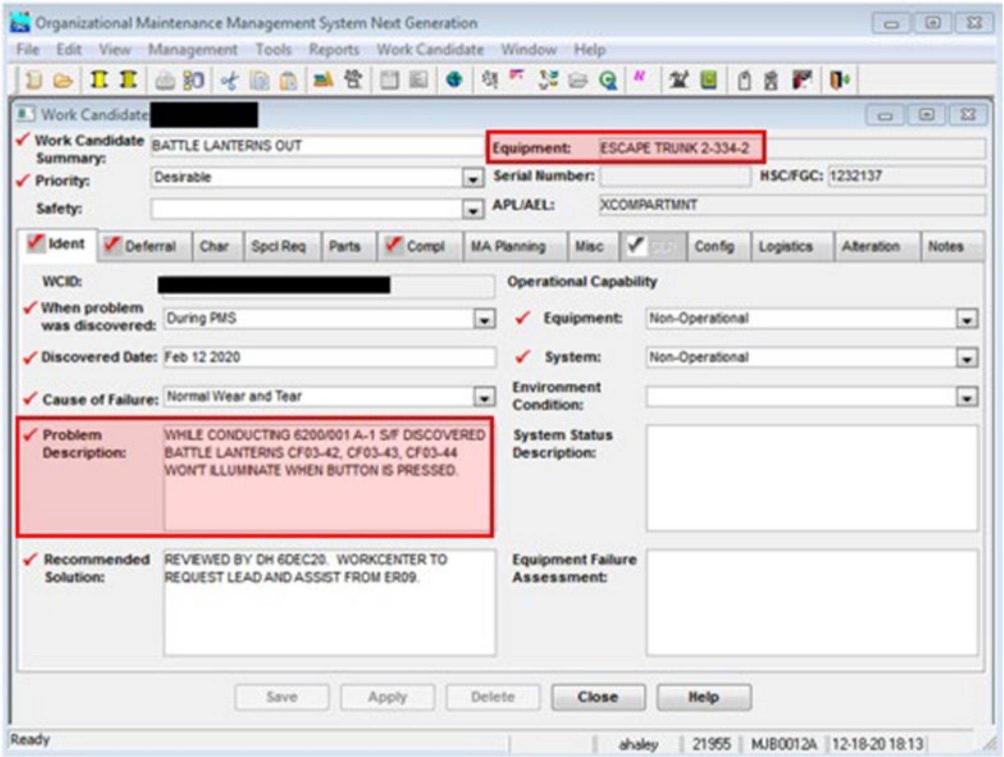


Figure 1. Work Candidate Example. Source: Wiltshire (2021).

Find the Following Items:

Item Name: Classroom Thermostat

Location Description:

This classroom thermostat is approximately 3" by 2" in size. Located on the left bulkhead of the classroom upon entry and near the secondary exit of the space. It is labeled "VAV-203".

Figure 2. Control Group Item Information Used. Source: Wiltshire (2021).

III. EXPERIMENTAL DESIGN

A. DESIGN OF STUDY

A 2x2 mixed design was chosen for this experiment, in order to match previous research that investigated the benefits of AR in locating objects in NPS laboratory spaces (Wiltshire, 2021). The first independent variable was the availability of AR technology. This was the between-subjects condition, with two levels: no AR headset (Control group) and AR headset (Experimental group). The second independent variable was the complexity of the environment which participants were searching. This was the within-subjects condition, with two levels: Simple Environment (represented by the Wardroom) and Complex Environment (represented by Shaft Alley and Sewage Plant Room #2). The dependent variables for all groups were time, measured in seconds, and accuracy, measured by a simple count of the number of items the participants correctly identified.

1. Physical Environment

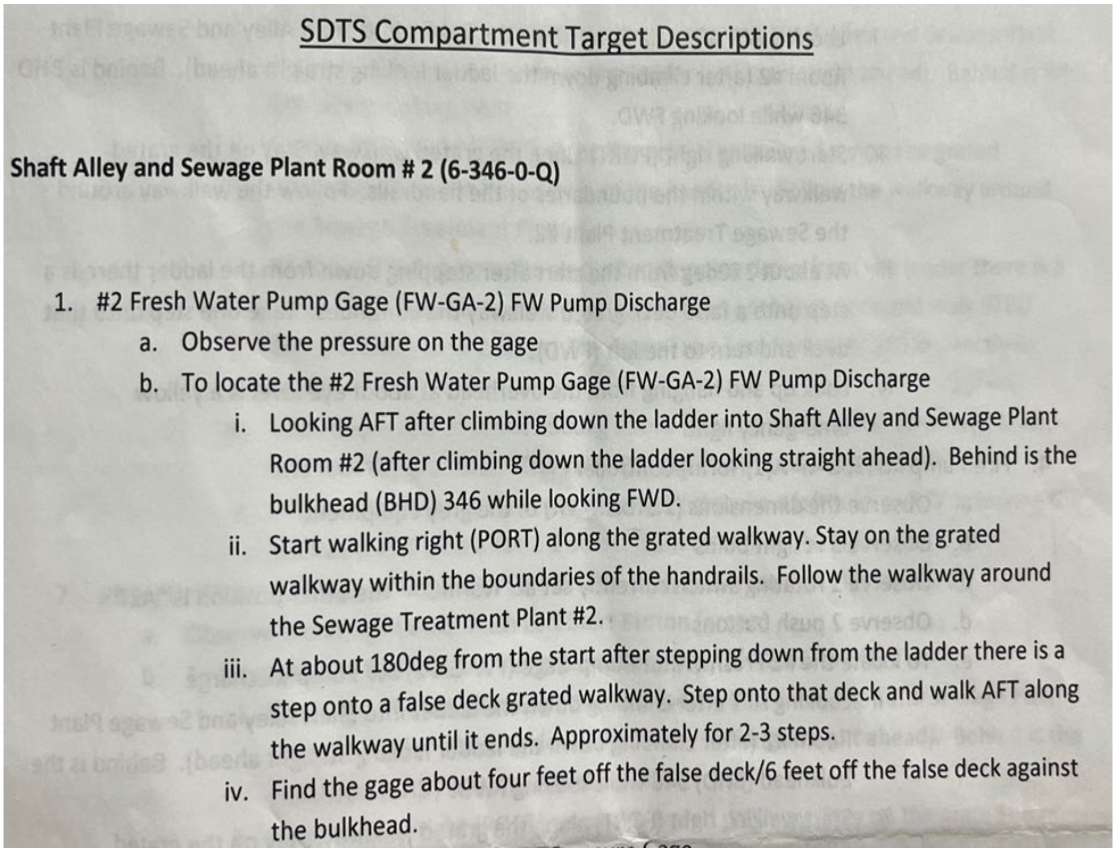
The experiment was conducted in two spaces aboard the SDTS that varied in terms of their complexity. This was done in order to align the experimental methods with those of Wiltshire (2021). For the simple space, the Wardroom of the SDTS was utilized (see Figure 3). For the complex space, the Shaft Alley and Sewage Plant Room #2 was utilized. The amount of maneuvering required to locate maintenance items and the number of differing maintenance items in a space were used to determine complexity. In each environment, 10 items were identified and provided to participants in list form to find.

This Wardroom is similar to the one on the SDTS, however, pictures of the actual SDTS cannot be shared due to distribution restrictions.

Figure 3. Wardroom of USS Cassin Young (DD 793). Source: Sundin (2015).

2. Participants

Ten participants were recruited for this study. The participants were recruited from the SDTS command, aged 25–58 years old (43.30 years old average), had military experience ranging from 0–23 years (average of 12.66 years), had maintenance experience ranging from 0–23 years (average of 10.61 years), and included five females, four males, and one individual of undisclosed sex. Six out of the 10 participants wore corrective lenses, six were enlisted sailors (E5-E9), three were government employees (GS12-GS14), and one individual did not disclose their rank. Finally, six out of the 10 participants had used virtual reality (VR) previously. The 10 participants were divided evenly and randomly assigned to one of two groups, the Control group and the AR group. Participants in the Control group were provided with written entries similar to actual work candidate location descriptions (see Figure 1). Due to the experimental focus on the benefits of AR versus evaluating the ineffectiveness of real work candidates produced under the current maintenance process, the descriptions provided to the control group were much more detailed than typical work candidate location descriptions, providing a full walkthrough from entering the space and leading the participant directly to the maintenance item. The work candidate location description is how outside activity would locate the maintenance item. Shown in the work candidate (Figure 1) is an example of where the location description would be written and shown below is an example of the location descriptions that the research team used for the experiment (Figure 4). The Control group represents the outside activity while the research team represented the originating work center, (i.e., party that owned the equipment and wrote the work candidate) who would enter the location description of the maintenance item.



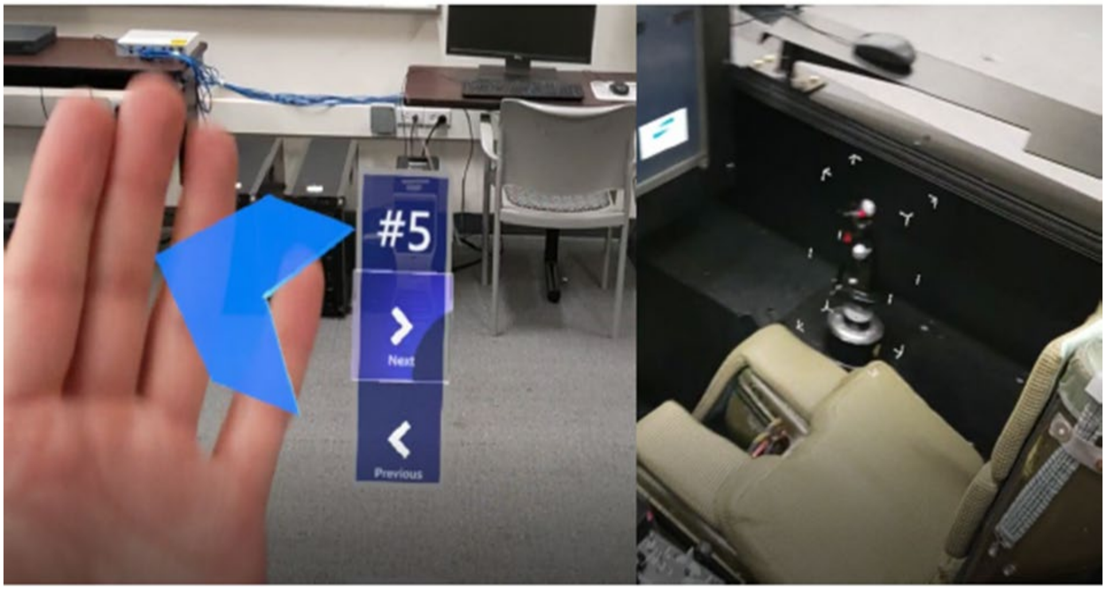
SDTS Compartment Target Descriptions

Shaft Alley and Sewage Plant Room # 2 (6-346-0-Q)

1. #2 Fresh Water Pump Gage (FW-GA-2) FW Pump Discharge
   a. Observe the pressure on the gage
   b. To locate the #2 Fresh Water Pump Gage (FW-GA-2) FW Pump Discharge
      i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is the bulkhead (BHD) 346 while looking FWD.
      ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.
      iii. At about 180deg from the start after stepping down from the ladder there is a step onto a false deck grated walkway. Step onto that deck and walk AFT along the walkway until it ends. Approximately for 2-3 steps.
      iv. Find the gage about four feet off the false deck/6 feet off the false deck against the bulkhead.

Figure 4. Control Group Location Description

The AR group used virtual aids in the form of Heads-Up symbology and directions projected through the Microsoft HoloLens 2, and therefore did not receive any written location descriptions. The only information that was provided was the item’s name. The AR headset would show the number of the item, a blue virtual directional arrow that aided the participant to orient themselves in the correct direction until the item was within view, and finally a white virtual box around the item (see Figure 5).



Above are two screenshots of the view that the participant saw through the AR headset. The blue directional arrows point in the direction of the item and the item is highlighted by a white box.

Figure 5. AR Group View

3. Surveys

A demographic survey (see Appendix B Demographic Survey) was filled out by participants prior to beginning the experiment. There were 10 questions to record each participant's age, gender, preferred writing hand, corrective lenses usage, military experience, experience with maintenance, experience playing computer games, experience with VR, and proneness to motion sickness.

A post-task survey (see Appendix C Post-Task Survey) was filled out by each participant after completion of the experiment in both spaces. The survey assessed the participant's perceived ease of task completion, perceived ease of understanding location descriptions of objects (i.e., written for the control group and visual for the AR group), and their most and the least difficult object to find in each space.

4. Hardware

The AR headset used was a Microsoft HoloLens 2 (Figure 6). This headset was chosen due to its availability through the NPS Modeling Virtual Environments and

Simulation (MOVES) department and the prior work that had been completed creating the virtual interface and back-end software to support the AR search task (Wiltshire, 2021).

Figure 6. Microsoft HoloLens 2. Source: Microsoft (2020).

5. Software

The software supporting the AR search task was developed by the NPS Future Tech Team and previously used by Wiltshire (2021) to test participants in NPS laboratory spaces. The key feature of the software is the creation and ability to view persistent tags of objects in 3D space using Unity coding language projected by the HoloLens 2. The application allowed the researcher to create white "bounding boxes" that were customizable in size and whose position could be adjusted and rotated as needed to tailor them to the objects being tagged. The application also included blue directional arrows that would point in the direction of the tagged object until the participant oriented themselves such that it was in their field of view (see Figure 5).

B. PROCEDURES

1. Main Experiment

Each participant found 10 items in the simple space (Wardroom) followed by 10 items in the complex space (Shaft Alley and Sewage Plant Room #2). The 20 items and the space they were located in are shown in Table 1. The Control group used the written descriptions to find items, while the AR group used the AR headset's visual cues to find items. Participants had to find items in the order that they were listed. They could not progress to the next item until finding the current item or running out of time. The order of items was consistent for all participants with no randomization from trial to trial. The research team recorded the time it took each participant to find each maintenance item in seconds, with a maximum time of 180 seconds, and whether they correctly identified the item. If participants failed to find an item within the time limit, the entry was recorded as "did not finish" (DNF). A research team member accompanied the participant throughout testing to confirm accuracy of item identification and to record the time. The participant would vocally confirm information needed to determine if the correct item was found. The data were recorded on paper during the experiment due to the impracticality and potential danger to the research team member of following participants through ship spaces carrying a computer or tablet. After each participant completed their trials, the research team member entered the data into an Excel spreadsheet for later analysis.

Table 1. Table of Objects Used as Maintenance Items

Item #	Item Description	Search Space
1	Polycom Voice Console	Simple
2	Thermostat	Simple
3	Fan Control Unit (FCU-R01-270-1) Motor Controller #4	Simple
4	Calendar (1st of May)	Simple
5	Computer and Electrical Outlet	Simple
6	Hatch, SS Generator Intake Trunk #2 (O1-306-1 SS GEN INTAKE TRK NO.2)	Simple
7	Tom Clancy "Rainbow" Book	Simple
8	1MC Loud Speaker	Simple
9	Panasonic TV Display (On/Off Switch)	Simple
10	Window Hatch O1-281-1	Simple
21	#2 Fresh Water Pump Gage (FW-GA-2) FW Pump Discharge	Complex
22	3-GTG-GA-1 Gen NR3 SW Pump Discharge Pressure Gage	Complex
23	Emergency Light (Yellow)	Complex
24	Fire Pump #6 (35B-4P-A(1)Norm) Controller	Complex
25	PL675 Graywater Valve, Tank XFR to Shore CON	Complex
26	SWS 318 Valve Stern Tube Seal Vent STBD	Complex
27	#2 Fresh Water Pump Local Controller (3-422-2)-4-B(1), Fed From Pwr PNL (3-422-2)	Complex
28	3A Pump Graywater Emergency Shutoff Switch	Complex
29	L/O Oil Check Point on the Stern Tube Seal Seawater Port	Complex
30	Brominator NR1 Pump Local Controller	Complex

2. Post Experiment

Once a participant completed the experiment, they were given the post-task survey. The experiment's end was marked by the completion of the post-task survey and debrief. Control group participants were able to demo the AR headset after completion, but no data was collected.

IV. RESULTS

A. DEMOGRAPHICS

Ten participants were recruited for the study on the SDTS. They were a mix of enlisted personnel and government contractors, representing the normal distribution of ship's company and outside activity who would be involved in locating maintenance items during the validation of maintenance item descriptions prior to a maintenance availability. The demographic breakdown is shown in Table 2.

Table 2. Demographic Breakdown of Participants

		Control	AR
Total Number		**5**	**5**
Age	Min	25	35
	Mean	36.4	50.2
	Max	50	58
Sex	Male	1	3
	Female	3	4
	Unknown	1	0
Years of Active Duty Service	Min	7	0
	Mean	15.52	9.8
	Max	21	23
Highest Rank	E5	1	1
	E6	1	0
	E7	1	1
	E9	0	1
	GS12	1	1
	GS14	1	0
	Unknown	0	1
Required to identify maintenance items as part of normal duties (%)	Yes	80%	100%
	No	20%	0%
Number of years of maintenance experience	Min	0	1.5
	Mean	9	12.625
	Max	16	23
Experienced VR (%)	Yes	60%	60%
	No	40%	40%

One participant provided incomplete demographic data, omitting their sex. Additionally, one participant was a government contractor and thus reported zero years in active duty service, no experience conducting maintenance as part of their normal duties, and no years of military maintenance experience.

B. HYPOTHESIS TESTING

The two research questions this thesis sought to answer were: (I) Does the use of augmented reality to identify maintenance items increase efficiency, both in terms of time and accuracy, compared to the current process? and (II) Does the use of augmented reality to identify maintenance items improve the accuracy and time of identification to a similar extent in both Simple and Complex shipboard spaces?

We formulated four hypotheses to investigate these questions, grouped into three categories: Accuracy, Time, and Search Space Complexity. The analyses of our experimental data will be organized by these hypotheses. For all analyses, our selected alpha (α) criterion was .01.

1. Accuracy

Our first hypothesis ($H1_A$) was that the AR group would have a higher overall mean accuracy than the Control group. The null hypothesis ($H1_0$) was that there would be no difference in mean accuracy between the AR group and the Control group. Accuracy was measured by counting the number of correctly identified maintenance items. Incorrect items were those that the participant either misidentified (e.g., they were supposed to find the Graywater Valve but instead found a Fuel valve), or items which the participant failed to find within the 180-second time limit.

When calculating the group means and standard deviations, we found that every single participant in the AR group correctly identified all 20 objects (10 objects in the Simple space and 10 objects in the Complex space), whereas participants in the Control group committed, on average, 5 errors across the two search spaces (see Table 3).

Table 3. Mean and Standard Deviation of Accuracy for Hypothesis 1

Condition	Mean Accuracy (# of accurately identified items)	Standard Deviation
AR	20	0
Control	15	2.74

Mean number of maintenance items located per participant and standard deviation for the AR and Control group, regardless of the complexity of the search space. There were 10 objects to find in the Simple space and 10 in the Complex space, thus the maximum number of correct items any participant could find was 20.

As the accuracy data was categorical, that is, the data reflected a tally of participants either 'correctly' or 'incorrectly' identifying maintenance items, we utilized Pearson's chi-squared statistic to test the homogeneity of the two groups' mean accuracy and found them to be significantly different ($\chi^2 = 28.57$, $p < .01$). This relationship is illustrated in Figure 7 as a mosaic plot, and in Figure 8 the JMP Pro Pearson chi-square test output can be found.

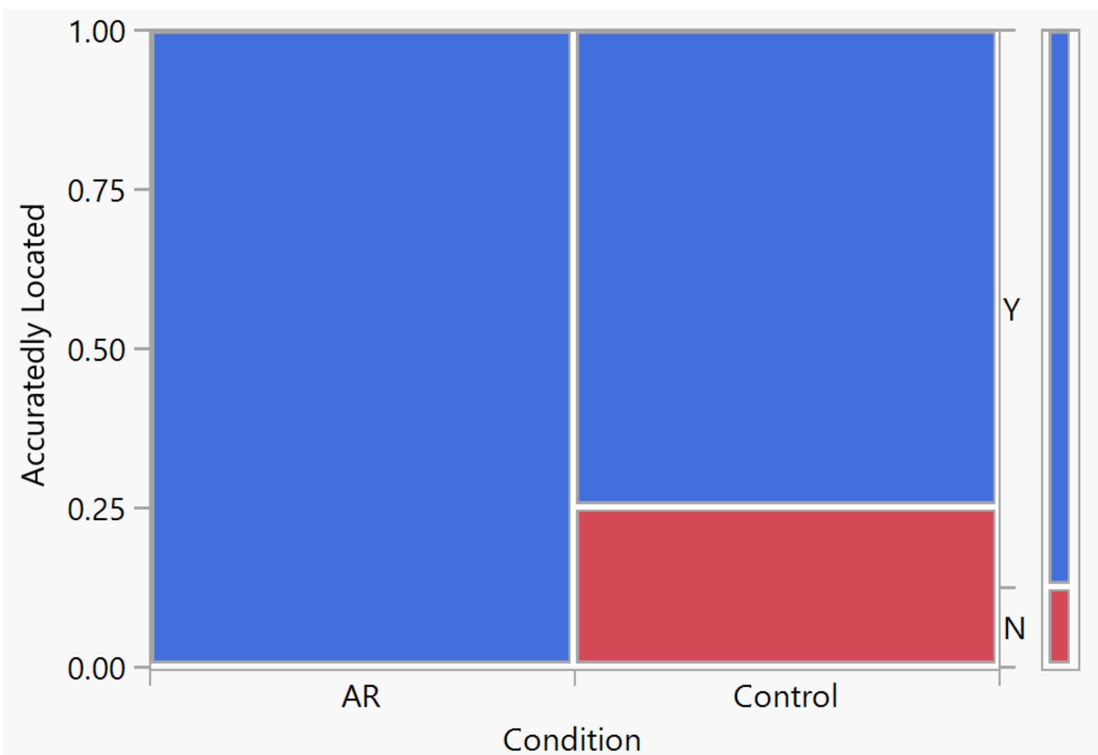


Figure 7. JMP Pro Output of Mosaic Plot of AR Versus Control Group Accuracy

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	38.241	<.0001*
Pearson	28.571	<.0001*

Figure 8. JMP Pro Output of Pearson Test for Hypothesis 1

2. Time

Our second hypothesis ($H2_A$) was that the AR group would have an overall lower mean search time, measured in seconds, than the Control group. The null hypothesis ($H2_0$) was that there would be no difference in time spent locating maintenance items between the AR group and the Control group.

When calculating the group means and standard deviations, we observed the AR group spent, on average, 77% less time than the Control group locating the maintenance items and that the two groups exhibited vastly different standard deviations (see Table 4).

Table 4. Mean and Standard Deviation of Search Time for Hypothesis 2

Condition	Mean Search Time (seconds)	Standard Deviation
AR	11.81	6.21
Control	51.66	37.59

Mean time to locate maintenance items (seconds) and standard deviation for the AR and Control group regardless of the complexity of the search space.

Therefore, we tested for unequal variances between the two groups and confirmed this via Welch's ANOVA, $F = 97.66$, $t = 9.88$, $p < .01$* (see Figure 9 for *p*-statistic as calculated by JMP).

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
97.6618	1	92.286	<.0001*

t Test
9.8824

Figure 9. JMP Pro Output of Tests for Unequal Variances for Hypothesis 2

The unequal variances between the two groups violates one of the assumptions of the Student's t-test, specifically, the assumption that both samples have homogeneous variances. Thus, we chose to compare the group means using the Wilcoxon (Rank-Sum) test and found a statistically significant difference between the group means, $Z = 10.13$, $p < .01$* (see Figure 10 for *p*-statistic as calculated by JMP).

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
AR	100	5697.00	9500.00	56.970	-10.130
Control	89	12258.0	8455.00	137.730	10.130

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
12258	10.12951	<.0001*

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
102.6340	1	<.0001*

Figure 10. JMP Pro Output of Wilcoxon Test for Hypothesis 2

These analyses confirm that overall, the Control group took significantly longer than the AR group to locate maintenance items.

3. Search Space Complexity

Our third hypothesis and fourth hypotheses expand upon our previous findings regarding overall Accuracy and Time by investigating whether the benefits of AR technology over the current method are the same in Simple and Complex search spaces.

Our third hypothesis ($H3_A$) predicted that AR technology would provide a greater benefit, reflected by a greater time savings, in a Complex space rather than a Simple space. To clarify, we predicted that the mean search time for the AR group would not be significantly different in the Complex space compared to the Simple space, however, the mean search time for the Control group would be considerably worse in the Complex space compared to the Simple space. The null hypothesis ($H3_0$) was that there would be no difference in search time between the AR group and the Control group, regardless of the complexity of the search space.

When calculating the group means and standard deviations, we found the AR group performed similarly in both the Simple and Complex search spaces, as seen in Table 5 and by visualizing the data as a box plot in Figure 11. Given this performance, we used the Student's t-test to compare the mean search time of the AR group in the Simple space versus the Compared space and found no significant difference, $t(96) = 0.82$, $p = .41$ (see Figure 12 for JMP Pro calculated output of Student's t-test for AR group).

Table 5. Mean and Standard Deviation of Search Time between the Simple and the Complex Space for Hypothesis 3

Search Space Complexity	Condition	Mean Search Time (seconds)	Standard Deviation
Simple	AR	11.30	6.63
	Control	30.07	17.85
Complex	AR	12.32	5.79
	Control	76.93	38.98

Mean time to locate maintenance items (seconds) and standard deviation for the AR and Control group in the Simple ship space (Wardroom) and the Complex ship space (Shaft Alley/Sewage Plant #2).

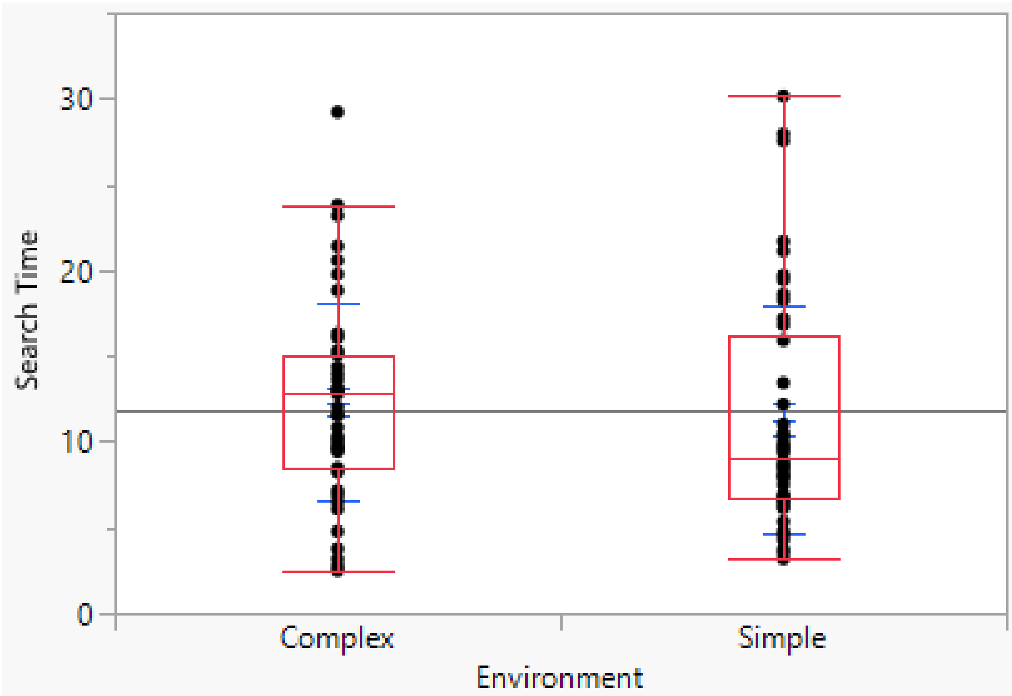


Figure 11. JMP Pro Output of Box Plot of AR Group's Mean Search Time in the Complex Versus Simple Search Space

t Test

Simple-Complex

Assuming unequal variances

Difference	-1.0220	t Ratio	-0.82089
Std Err Dif	1.2450	DF	96.25935
Upper CL Dif	2.2497	Prob > |t|	0.4137
Lower CL Dif	-4.2937	Prob > t	0.7931
Confidence	0.99	Prob < t	0.2069

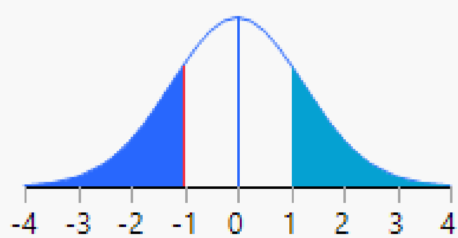


Figure 12. JMP Pro Output of Student's T-test Comparing Mean Search Time for the AR Group in the Complex Versus Simple Search Space

As seen in Table 5, however, the Control group exhibited vastly different mean search time and standard deviation in the Simple space compared to the Complex space. This disparity is additional visualized in a box plot in Figure 13.

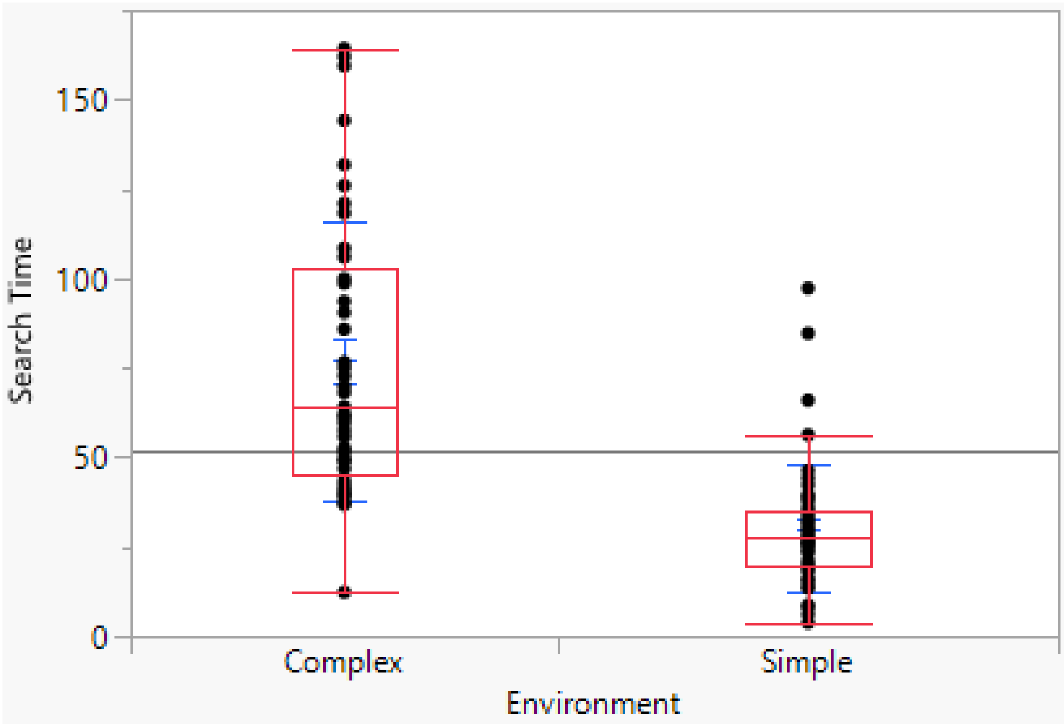


Figure 13. JMP Pro Output of Box Plot of the Control Group's Mean Search Time in the Complex Space Versus the Simple Space

Given these apparent differences, Welch's ANOVA was used to verify whether the Control group's mean search times in the different search spaces had unequal variances, $F = 50.25$, $t = 7.09$, $p < .01$* (see Figure 14 for the JMP Pro Welch Test output for the Control group's mean search time).

Welch's Test

Welch Anova testing Means Equal, allowing Std Devs Not Equal

F Ratio	DFNum	DFDen	Prob > F
50.2455	1	54.137	<.0001*

t Test
7.0884

Figure 14. JMP Pro Output of Welch's Test for Unequal Variances for the Control Group's Mean Search Time in the Simple Space Versus the Complex Space

As the unequal variances between the two groups means violates the assumption of equal sample variances of the Student's t-test, we chose to run the Wilcoxon (Rank –Sum) test and found a statistically significant difference between the group means, $Z = 6.73$, $p < .01^*$ (see Figure 15 for the JMP Pro Wilcoxon test output for the Control group's mean search time).

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Expected Score	Score Mean	(Mean-Mean0)/Std0
Complex	41	2663.00	1845.00	64.9512	6.729
Simple	48	1342.00	2160.00	27.9583	-6.729

2-Sample Test, Normal Approximation

S	Z	Prob>|Z|
2663	6.72891	<.0001*

1-Way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
45.3336	1	<.0001*

Figure 15. JMP Pro Output of Wilcoxon Test for the Control Group's Mean Search Time in the Simple Versus Complex Search Space

These analyses allow us to reject $H3_0$ and confirm that the time-saving benefits of AR technology over the current method (i.e., reading written instructions), while significant in Simple spaces, are far more apparent in Complex ship spaces. This result is particularly compelling as most maintenance delays are caused by the inability for outside activity to follow the work candidates written by ship's force, precisely in the Complex spaces of surface vessels (Maurer, 2020).

Finally, our fourth hypothesis ($H4_A$) was that AR technology would provide a greater benefit, reflected by a greater reduction in inaccuracies, when identifying maintenance items in a Complex space compared to a Simple space. To clarify, we predicted that the Control group would be significantly less accurate when searching for maintenance items in the Complex space compared to in the Simple space. We defined an inaccuracy as maintenance items that were either misidentified or were not located within a 180-second time limit. The null hypothesis ($H4_0$) was that there would be no difference in mean accuracy for the Control group regardless of the complexity of the search space.

When calculating the group means and standard deviations, we found that the AR group performed perfectly across both Simple and Complex spaces. That is, all participants in the AR group located all 10 items in the Simple space and all 10 items in the Complex space, with no misidentifications or time-outs. In contrast, the Control group committed, on average, 1.6 more errors than the AR group in the Simple space and 3.4 more errors than the AR group in the Complex space (see Table 6).

Table 6. Mean and Standard Deviation of Accuracy between the Simple and the Complex Space for Hypothesis 4

Search Space Complexity	**Condition**	**Mean Accuracy (# of accurately identified items)**	**Standard Deviation**
Simple	AR	10	0
	Control	8.4	0.89
Complex	AR	10	0
	Control	6.6	2.07

Mean number of maintenance items located and standard deviation for the AR and Control group, in the Simple and the Complex spaces. There were 10 objects to find in the Simple space and 10 in the Complex space.

As there was no difference in mean accuracy or standard deviation for the AR group in both the Simple and Complex spaces, no analysis was conducted. However, the Control group exhibited, on average, more errors when searching for items in the Complex space than in the Simple space. As the accuracy data was categorical, that is, the data reflected a tally of participants either ‘correctly’ or ‘incorrectly’ identifying maintenance items, we utilized Pearson’s chi-squared statistic to test the homogeneity of the two groups’ mean accuracy, $\chi^2 = 4.32$, $p = .03$. This result fails to meet our selected α of .01, therefore we cannot reject $H4_A$. The relationship of this data is depicted as a Mosaic plot in Figure 16, while the JMP Pro Pearson chi-square test output can be found in Figure 17. In sum, we found that the Control group, relying on the current practice of reading written instructions in work candidates, committed more inaccuracies in the Complex Space compared to in the Simple Space, but we were not able to reject the Null hypothesis ($H4_0$). Possible causes for this will be explored in the Discussion section.

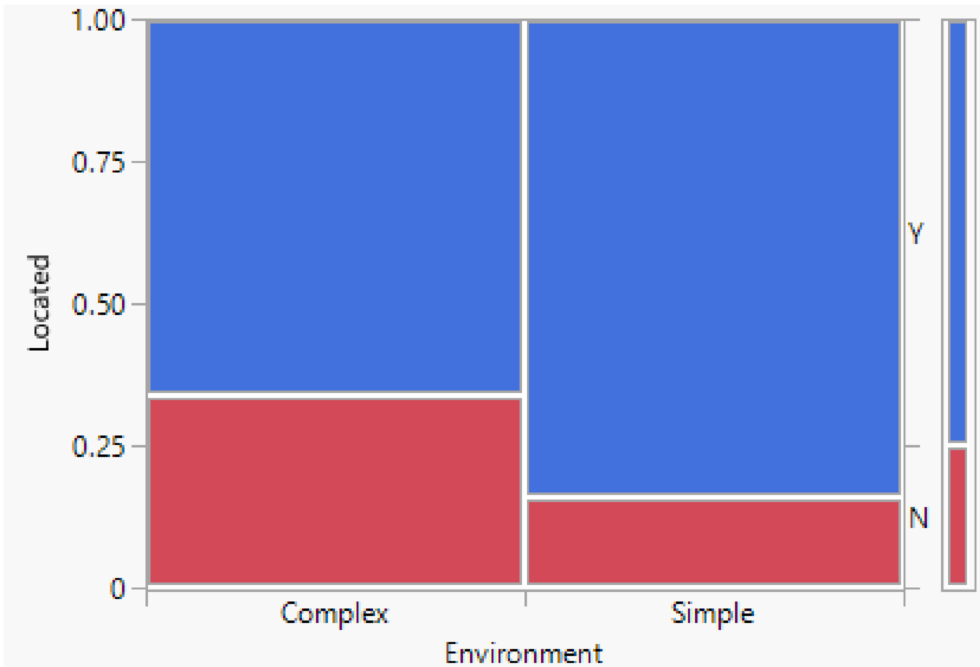


Figure 16. JMP Pro Output of Mosaic Plot for Control Group Mean Accuracy in the Complex Space Versus the Simple Space

Test	ChiSquare	Prob>ChiSq
Likelihood Ratio	4.396	0.0360*
Pearson	4.320	0.0377*

Figure 17. JMP Pro Output of Pearson Chi-square Test for the Control Group in the Complex Space Versus the Simple Space

V. DISCUSSION

A. IMPACT OF FINDINGS

The results demonstrate AR technology significantly increased accuracy compared to the current process (i.e., reading written instructions) as all participants in the AR group found 100% of the maintenance items, regardless of the complexity of the search space. AR technology additionally allowed participants to spend significantly less time identifying maintenance items compared to the current process. Finally, the time savings realized by AR technology over the current process was much more pronounced in the Complex space compared to the Simple space.

During actual maintenance availabilities, these time savings afforded by AR technology would translate to cost savings through a reduction in outside activity (i.e., contractors that charge their time) failing to identify or locate maintenance items within a reasonable time. As such, implementing AR technology would eliminate a significant cause of delays in maintenance availabilities.

The timely identification of maintenance items also impacts cost creep, as discussed by Maurer (2020). Essentially, maintenance items that are not located in a timely manner or identified at all cannot be included in the initial maintenance contract, as per CNO (2019, p. 2-2). However, when these items are eventually found, they are logged as “new work” or “growth work” (as these items still have to be fixed in order for the vessel to be mission capable). The process of logging “new work” or “growth work” involves additional contracting, adding costs and further delaying the availability of the ship for the surface fleet’s mission.

An additional benefit that AR technology could provide is standardizing work candidates. In other words, rather than utilizing work candidates of varying quality and descriptiveness that are generated by ship’s force to describe the location and discrepancy with the maintenance item, AR technology allows for a single, high-quality work candidate (with an integral digital tag of the item) to be created. This can then be carried forward throughout the maintenance availability. This robust, error-free work candidate would ensure the continued ability for many different outside activities to quickly and accurately locate items prior to and during maintenance availabilities, saving considerable costs over the life cycle of the ship and reducing the additional costs associated with missed items that are later logged as "new work" or "growth work."

Finally, by confirming $H3_A$, we show that the greatest time-savings benefits of AR technology are in Complex spaces as opposed to Simple spaces. While a wide variety of maintenance items have to be located during an availability, the greatest delays result from those items that are in Complex ship spaces. Complex spaces, such as the Shaft Alley/ Sewage Plant #2 utilized in our study significantly increase the time to locate items and introduce a number of obstructions in space that ship's force and outside activity have to orient themselves to and then navigate through (see Table 5 for time and Table 6 for accuracy). Thus, AR technology would provide tangible time and cost savings even if it were only implemented in complex spaces around the ship (i.e., engineering spaces and combat systems spaces). Another important aspect is that users were able to do a one-minute training and able to achieve zero errors and time savings. This means that minimal training is needed to implement the usage of this with the Ship's Force and outside activity.

B. LIMITATIONS

Our primary limitation was our limited pool of participants. Due to the operational constraints for the SDTS, we were only able to recruit 10 participants. This lack of participants likely impacted our inability to reach statistical significance, preventing us from rejecting $H4_0$ and confirming that the benefits of AR, in terms of accuracy, were greater in Complex spaces than in Simple spaces.

However, despite our overall lack of participants, our participants' demographics reflected the actual personnel that would normally be involved in the maintenance process, especially in identifying maintenance items (60% military enlisted and 40% government contractors). This allowed us to see the benefits of using AR over the current process with personnel who have the same qualifications and experience as actual ship's force and outside activity who would be tasked to identify maintenance items during an availability. This is exemplified by the fact that the Control group had, on average, nine years of maintenance experience yet still struggled to identify objects accurately and quickly, even when provided with our location descriptions that were far more detailed than actual current work candidates (see Figure 2 and Figure 4).

An additional limitation was that our objects used as maintenance items were not vetted through a subject matter expert (SME) to verify an equal distribution of difficulty in identifying maintenance items. Future research could utilize SME input to generate a list of objects that contained an equal number of easy, moderate, and difficult-to-locate items. Alternatively, SMEs could be used to generate lists of only moderate, or difficult-to-locate items to specifically study the benefits of AR, as measured by time and accuracy, on the hardest-to-find maintenance items in the most complex spaces of a surface vessel. To illustrate this limitation, in Figure 18, Objects 1–10 represent the 10 maintenance items that had to be located in the Simple space. In Figure 19, Objects 21–30 represent the 10 maintenance items that had to be located in the Complex space. As a reminder, participants had to locate items in order and could not skip ahead in the list. Regardless of the complexity of the search space, the AR group had 100% accuracy in locating all maintenance items. For the Control group in the Simple space, the hardest-to-locate item was object #8 (1MC Loud Speaker), with only 40% accuracy (see Figure 18). For the Control group in the Complex space, the hardest-to-locate item was object #25 (PL675 Greywater Valve, Tank XFR to Shore CON), with 0% accuracy (see Figure 19).

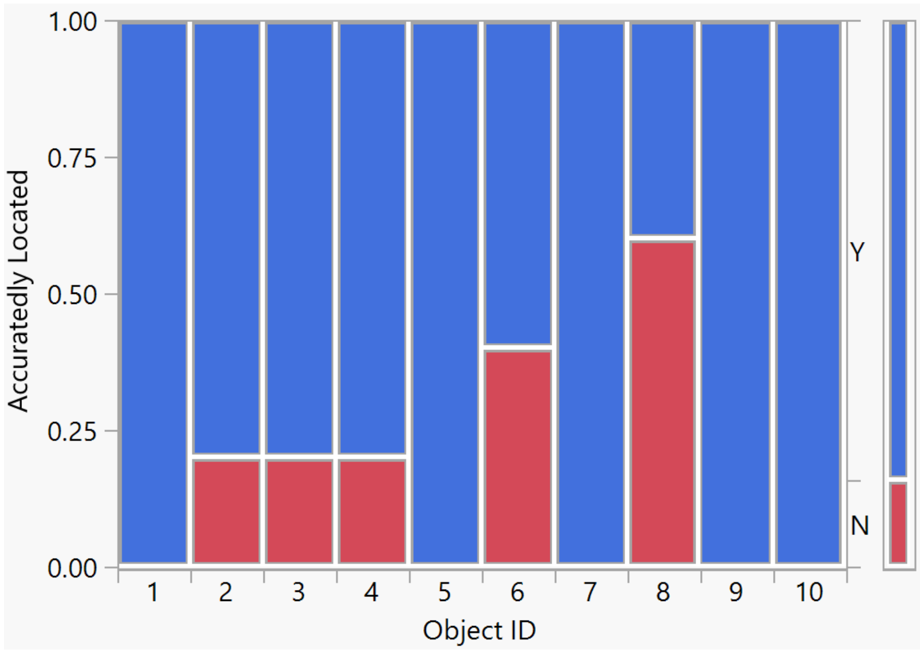


Figure 18. JMP Pro Output of Mosaic Plot of Accuracy Broken Down by Each Item in the Simple Space

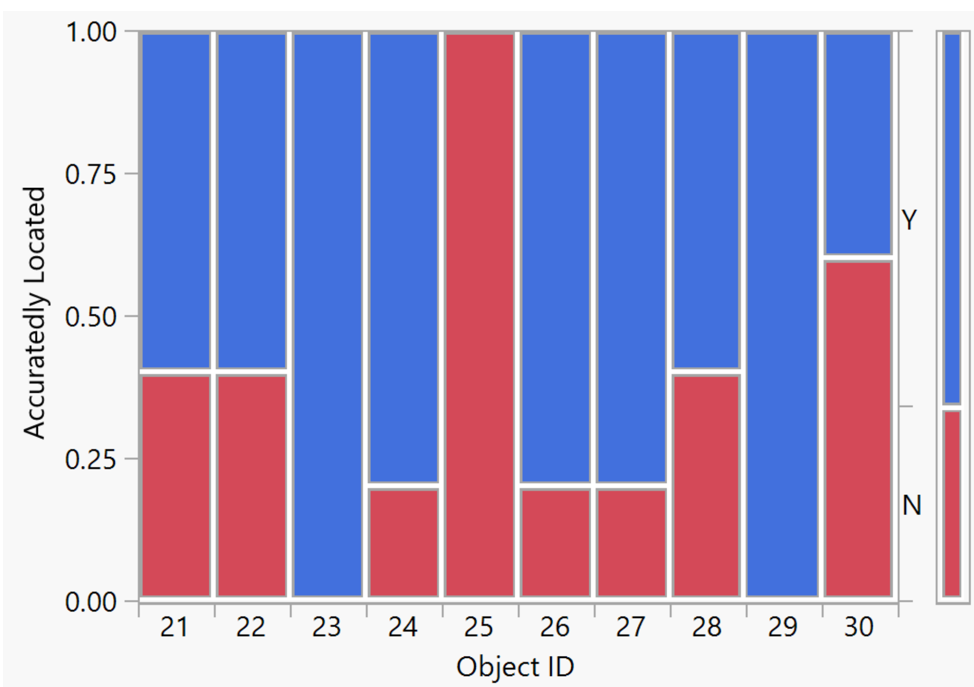


Figure 19. JMP Pro Output of Mosaic Plot of Accuracy Broken Down by Each Item in the Complex Space

C. FUTURE RESEARCH

In the following section I will discuss potential future research with AR technology in maintenance availabilities and the implications of that research.

First, experiments to test conducting an Equipment Validation (EQV) should be conducted. An EQV is similar to our experiment except instead of locating 10 items in a space, personnel have to find every single item contained inside the space and verify details about the item. Each division on a ship has to conduct EQVs on every space that they have accountability for within a 36-month cycle, and this is repeated until the decommissioning of the ship. Extrapolating the time savings from using AR in the current methodology, multiplied by the large number of items that need to be accounted for during an EQV, would save the Navy Surface Fleet thousands of man-hours and millions of dollars each year.

Next, our AR software could be further developed to include maintenance procedures, displayed as digitized visualizations of the required movements, paired with written directions and warning labels. Such efforts are already under development by NPS MOVES researchers (Angelopoulos & Greunke, 2021). Studies using our methodology, supplemented by these digitized visualizations, could be conducted in a training environment to investigate whether we could speed the buildup of maintainers' knowledge base to conduct complex maintenance unaided.

Third, we have yet to assess ARs ability to assist ship's force in familiarizing themselves to new layouts. This could assist new Sailors and Officers with learning complex spaces, such as engineering and combat spaces. An extension of this line of effort could include implementing a 3D interactive map that could be manipulated within the AR headset, and hand gestures to explore the different levels and spaces of the ship. It often takes a few weeks to familiarize oneself with new complex spaces on ships; reducing the length and difficulty of this learning period would yield operational and cost benefits.

Finally, a critical area to study is ARs benefit to ship's force during Damage Control events (i.e., fire or flooding in a space). AR technology could be used to identify valves and other materials necessary to isolate events and solve them. Further, AR could be used to place digital tags for referencing information, allowing responders to see critical items such as valves through obstructions like flooding and smoke.

APPENDIX A. MAINTENANCE ITEM LOCATION DESCRIPTIONS

A. SIMPLE SPACE (WARDROOM)

Wardroom

1. Polycom voice console
   a. To locate Polycom voice console upon entering the Wardroom through the AFT door walk toward STBD side of the room along the AFT main table.
   b. The console is on top of the table in the center.
2. Thermostat
   a. To locate the Thermostat upon entering the Wardroom through the AFT door turn left (FWD) and immediately observe the thermostat on the bulkhead at approximately FR 292 two feet away from the entrance.
   b. The Thermostat is about 6 feet off the deck.
3. Fan Control Unit (FCU-R01-270-1) Motor controller #4

a. To locate Fan Control Unit upon entering the Wardroom through the AFT door walk toward STBD side of the room along the AFT main table until reaching the STBD bulkhead of the Wardroom.
b. The FCU is an equipment housing about 2X2 feet.
c. There are two motor controllers indicators and push buttons on the FCU face plate.
d. Locate Motor Controller #4 which has a lit indicator and an on/off button below it. The Motor Controller #2 has a Danger Tag in the off position.

4. Calendar (1st of May)
    a. To locate the calendar upon entering the Wardroom through the FWD door turn right (AFT) and observe the calendar on the Port bulkhead at approximately FR 287 10 feet away from the entrance.
    b. Locate May 1st on the calendar
5. Computer and Electrical Outlet
    a. To locate the outlet upon entering the Wardroom through the FWD door walk toward STBD side of the room along the FWD main table.
    b. The outlet is on top of the table in the center.
    c. If the outlet is hidden or flush with the table, then push the black rectangle to lift and expose the outlet.
6. Hatch, SS Generator Intake Trunk #2 (01-306-1 SS GEN INTAKE TRK NO.2)
    a. To locate the Hatch upon entering the Wardroom through the AFT door turn right (AFT) and walk toward the AFT section of the divided Wardroom compartment.
    b. Walk diagonally toward STBD bulkhead FR 306.
    c. There are two hatches against the STBD bulkead.
    d. Locate the FWD hatch 01-306-1 SS GEN INTAKE TRK NO.2 handle and various nut/bolts.
7. Tom Clancy "Rainbow" book
    a. To locate the book upon entering the Wardroom through the AFT door turn right (AFT) and walk toward the AFT section of the divided Wardroom compartment.
    b. Walk along the dividing book shelves/TV console until reaching the STBD side book case (i.e. STBD of Center)
    c. The book is located in the 3rd shelve from the top and is the 3rd book from the right.
8. 1MC Loud Speaker
    a. To locate the calendar upon entering the Wardroom through the FWD door turn right (AFT) and walk along the Port bulkhead until reaching the FWD edge of the AFT main table. Approximately FR 287 10 feet away from the entrance.
    b. Turn left looking STBD.
    c. Look above into the overhead and located the 1MC Loud Speaker.
    d. Observe the 1MC's small black rotating volume controller. The 1MCs face plate is grey 12x8 inches.
9. Panasonic TV Display (on/off switch)
    a. To locate the display by entering the Wardroom through the FWD door walk toward STBD side of the room along the FWD main table.

b. Turn left (FWD) and observe 2 TV displays 3x5 feet. The target display is STBD of compartment centerline and on top of the drawer console.
c. Locate the on/off button on the left bottom corner of the display. The on/off button is noted with a universal marking. Next to the on/off button is an indicator that lights green when the button is in the on position.

10. Window Hatch 01-281-1
    a. To locate the calendar upon entering the Wardroom through the FWD door turn right (AFT) and walk along the Port bulkhead until reaching the AFT edge of the FWD main table. Approximately FR 281 3 feet away from the entrance.
    b. Turn left looking STBD and walk until reaching the STBD bulkhead.
    c. Observe the window hatch' damage control marking Delta Zebra.
    d. There are two window hatches in the same proximity. Window Hatch 01-281-1 is the FWD window.

B. COMPLEX SPACE (SHAFT ALLEY AND SEWAGE PLANT ROOM #2)

Shaft Alley and Sewage Plant Room # 2 (6-346-0-Q)

1. #2 Fresh Water Pump Gage (FW-GA-2) FW Pump Discharge
   a. Observe the pressure on the gage
   b. To locate the #2 Fresh Water Pump Gage (FW-GA-2) FW Pump Discharge
      i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is the bulkhead (BHD) 346 while looking FWD.
      ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.
      iii. At about 180deg from the start after stepping down from the ladder there is a step onto a false deck grated walkway. Step onto that deck and walk AFT along the walkway until it ends. Approximately for 2-3 steps.
      iv. Find the gage about four feet off the false deck/6 feet off the false deck against the bulkhead.
2. 3-GTG-GA-1 Gen NR3 SW Pump Discharge Pressure Gage
   a. Observe the calibration decal on the gage
   b. To locate the 3-GTG-GA-1 Gen NR3 SW Pump Discharge Pressure Gage
      i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is BHD 346 while looking FWD.
      ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.
      iii. At about 270deg from the start after stepping down from the ladder there is a step onto a false deck grated walkway. Step onto that deck and walk STBD along 270deg for 1-2 steps. The Stern Tube Seal Seawater STB is directly in front.
      iv. Follow the walkway around until it ends facing BHD 346 (FWD).
      v. Look for the grey gage at eye level.
3. Emergency Light (yellow)
   a. Observe the green lit indicator
   b. Push the push button on top of the light to test
   c. To locate the Emergency Light (yellow)

i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is BHD 346 while looking FWD.

ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.

iii. At about 270deg from the start after stepping down from the ladder there is a step onto a false deck grated walkway the continues. Take one step onto that deck and turn to the left (FWD).

iv. Look up and hanging from the overhead at about eye level is a yellow emergency light.

4. Fire Pump #6 (35B-4P-A(1)Norm) Controller
   a. Observe the dimensions (2.5ftx3ftx1ft) of the grey equipment
   b. Observe 3 lit light bulbs
   c. Observe 1 rotating switch currently set at "Normal". The other position is "ALT"
   d. Observe 2 push buttons
   e. To locate the #2 Fresh Water Pump Gage (FW-GA-2) FW Pump Discharge
      i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is the bulkhead (BHD) 346 while looking FWD.
      ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.
      iii. At about 200deg from the start after stepping down from the ladder there is a step onto a false deck grated walkway. Walk AFT along the walkway until it ends.
      iv. Find the controller against the bulkhead.
5. PL675 Graywater Valve, Tank XFR to Shore CON
   a. Observe Valve position is parallel to the pipe.
   b. To locate the PL675 Graywater Valve, Tank XFR to Shore CON
      i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is BHD 346 while looking FWD.
      ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.
      iii. At about 270deg from the start after stepping down from the ladder stop prior to stepping up onto the false deck grated walkway. The Stern Tube Seal Seawater STB is directly in front. Look up into the overhead to find the valve.
6. SWS 318 Valve Stern Tube Seal Vent STBD
   a. Observe valve position is parallel to the pipe.
   b. To locate the SWS 318 Valve Stern Tube Seal Vent STBD

        i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is BHD 346 while looking FWD.
        ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.
        iii. At about 270deg from the start after stepping down from the ladder there is a step onto a false deck grated walkway. Step onto that deck and walk STBD along 270deg for 1-2 steps. The Stern Tube Seal Seawater STB is directly in front.
        iv. Look diagonally at about 260deg above into the overhead at about eye level, and look for the valve. The valve is tagged with a round tag 'SWS 318".
        v. After a short two to three steps going Port make a left turn to AFT following the walkway, and stop after 1-2 steps. Turn to look to the right (Port).

7. #2 Fresh Water Pump Local Controller (3-422-2)-4-B(1), Fed From Pwr PNL (3-422-2)
    a. Observe the lit Light Bulb: Push Left Start Button (green)
    b. To locate the #2 fresh Water Pump Local Controller (3-422-2)-4-B(1)
        i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is the bulkhead (BHD) 346 while looking FWD.
        ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.
        iii. At about 180deg from the start after stepping down from the ladder there is a step onto a false deck grated walkway. Step onto that deck and walk AFT along the walkway until it ends. Approximately for 2-3 steps.
        iv. Find the controller along the bulkhead.
8. 3A Pump Graywater Emergency Shutoff Switch
    a. Observe position of rotating switch is in the Off position
    b. To locate the 3A Pump Graywater Emergency Shutoff Switch
        i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is BHD 346 while looking FWD.
        ii. Start walking right (PORT) along the grated walkway for one step.
        iii. Turn right to face FWD.
        iv. While facing FWD the switch controller is located at about 8 feet above the compartment deck and about 6 feet above the false grated deck.
9. L/O Oil Check Point on the Stern Tube Seal Seawater Port
    a. Observe check point to use a dip stick
    b. To locate the Stern Tube Seal Seawater (Port),

i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is BHD 346 while looking FWD.
ii. Start walking right (PORT) along the grated walkway.
iii. After a short two to three steps going Port make a left turn to AFT following the walkway, and stop after 1-2 steps. Turn to look to the right (Port). This is about 90deg from the start after stepping down from the ladder.
iv. The Stern Tube Seal Water is located in front.
    1. It is painted grey.
    2. It appears to be in two sections: 1) a half cylinder of about 3 feet in diameter interfaced to a rectangle base support foundation (both units are one piece).
    3. The L/O Oil Check Point is located on the bottom rectangular base section
        a. The L/O Check Point is capped and the cap has metal chain

10. Brominator No1 Pump Local Controller
    a. On/Off Switch currently in Off position (the switch is Tagged out)
    b. To locate the Brominator No1 Pump Local Controller
        i. Looking AFT after climbing down the ladder into Shaft Alley and Sewage Plant Room #2 (after climbing down the ladder looking straight ahead). Behind is the bulkhead (BHD) 346 while looking FWD.
        ii. Start walking right (PORT) along the grated walkway. Stay on the grated walkway within the boundaries of the handrails. Follow the walkway around the Sewage Treatment Plant #2.
        iii. At about 180deg from the start after stepping down from the ladder there is a step onto a false deck grated walkway. Step onto that deck and walk AFT along the walkway until it ends. Approximately for 2-3 steps.
        iv. Find the controller along the bulkhead.

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APPENDIX B. DEMOGRAPHIC SURVEY

Demographic Survey

Subject Number: _______ Date: _______

1.Age:

2. Gender: Female Male

3. Preferred writing hand: Left Right

4. Do you wear any corrective lenses: Yes No

   a. If yes: what is your uncorrected vision: ______ (example 20/400)

5. Are you currently serving in the Armed Forces: Yes No

   a. Which branch: USA USN USMC USAF USCG

   b. Years of Service: ______ (years, example 2.4)

   c. Highest Rank: ______ (example O3)

   d. Rating/MOS: ______ (example AN, AE; or service equivalent)

6. Has your job or military occupation required you to identify components for preventative or corrective maintenance? Yes No

7. Years involved with military maintenance to include supervision or management : ______

   (years, example 1.3)

8. How many hours a week do you play computer games? ______ (hours, ex. 1.2)

9. Have you ever experienced a virtual environment? Yes No

   b. If Yes: About how many times? _______________

10. Are you prone to motion sickness? Yes No

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APPENDIX C. POST-TASK SURVEY

Subject ID: Date:

Shipboard Augmented Reality Object Location Experiment

Post-task Survey: TRADITIONALLY GUIDED TASK (CONTROL)

1. Indicate how easy it was to complete the task overall:

    ☐ Very Easy

    ☐ Moderately Easy

    ☐ Neither Easy nor Difficult

    ☐ Moderately Difficult

    ☐ Very Difficult

2. Indicate how easy it was to understand the location descriptions of the objects overall:

    ☐ Very Easy

    ☐ Moderately Easy

    ☐ Neither Easy nor Difficult

    ☐ Moderately Difficult

    ☐ Very Difficult

    a. OPTIONAL: If you answered "Moderately Difficult" or "Very Difficult", please explain why: ____

    ____

3. What was the most difficult object to find for each room?

4. What was the least difficult object to find for each room?

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