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SUPPORTING MISSION PLANNING WITH A PERSISTENT AUGMENTED ENVIRONMENT

Turner, JaMerra S.; Cruz, Joanna F.

Monterey, CA; Naval Postgraduate School

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THESIS

SUPPORTING MISSION PLANNING WITH A PERSISTENT AUGMENTED ENVIRONMENT

by

JaMerra S. Turner and Joanna F. Cruz

September 2022

Thesis Advisor: Amela Sadagic
Second Reader: Michael J. Guerrero

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13. ABSTRACT (maximum 200 words)

The Department of the Navy relies on current naval practices such as briefs, chat, and voice reports to provide an overall operational assessment of the fleet. That includes the cyber domain, or battlespace, depicting a single snapshot of a ship's network equipment and service statuses. However, the information can be outdated and inaccurate, creating confusion among decision-makers in understanding the service and availability of equipment in the cyber domain. We examine the ability of a persistent augmented environment (PAE) and 3D visualization to support communications and cyber network operations, reporting, and resource management decision-making. We designed and developed a PAE prototype and tested the usability of its interface. Our study examined users' comprehension of 3D visualization of the naval cyber battlespace onboard multiple ships and evaluated the PAE's ability to assist in effective mission planning at the tactical level. The results are highly encouraging: the participants were able to complete their tasks successfully. They found the interface easy to understand and operate, and the prototype was characterized as a valuable alternative to their current practices. Our research provides close insights into the feasibility and effectiveness of the novel form of data representation and its capability to support faster and improved situational awareness and decision-making in a complex operational technology (OT) environment between diverse communities.

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SUPPORTING MISSION PLANNING WITH A PERSISTENT AUGMENTED ENVIRONMENT

JaMerra S. Turner
Lieutenant, United States Navy
BS, Hampton University, 2015

Joanna F. Cruz
Lieutenant, United States Navy
BSAE, Virginia Polytechnic Institute and State University, 2015

Submitted in partial fulfillment of the
requirements for the degree of

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September 2022

Approved by: Amela Sadagic
Advisor

Michael J. Guerrero
Second Reader

Gurminder Singh
Chair, Department of Computer Science

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ABSTRACT

The Department of the Navy relies on current naval practices such as briefs, chat, and voice reports to provide an overall operational assessment of the fleet. That includes the cyber domain, or battlespace, depicting a single snapshot of a ship's network equipment and service statuses. However, the information can be outdated and inaccurate, creating confusion among decision-makers in understanding the service and availability of equipment in the cyber domain. We examine the ability of a persistent augmented environment (PAE) and 3D visualization to support communications and cyber network operations, reporting, and resource management decision-making. We designed and developed a PAE prototype and tested the usability of its interface. Our study examined users' comprehension of 3D visualization of the naval cyber battlespace onboard multiple ships and evaluated the PAE's ability to assist in effective mission planning at the tactical level. The results are highly encouraging: the participants were able to complete their tasks successfully. They found the interface easy to understand and operate, and the prototype was characterized as a valuable alternative to their current practices. Our research provides close insights into the feasibility and effectiveness of the novel form of data representation and its capability to support faster and improved situational awareness and decision-making in a complex operational technology (OT) environment between diverse communities.

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
AAR	After-Action Report
AOR	Area of Responsibility
AR	Augmented Reality
ASW	Antisubmarine Warfare
AVS	Advanced Visualization System
AW	Air Warfare
AWT	Aircrew Weapons Training
BMD	Ballistic Missile Defense
BWC	Battle Watch Captains
CASREP	Casualty Report
CDR	Commander
CG	Cruiser
CO	Commanding Officer
COA	Course of Action
CoC	Chain of Command
COMMO	Communications Officer
COMMPLAN	Communications Plan
COMMSPOT	Communication Spot
COP	Common Operational Picture
CRUDES	Cruisers or Destroyers
CSA	Cyber Situational Awareness
CSG	Carrier Strike Group
CSO	Combat Systems Officer
CVE	Collaborative Virtual Environment
CVN	Carrier, Fixed-Wing Aircraft, Nuclear
CW	Cryptologic Officer
CWC	Composite Warfare Commanders
DC	Damage Control
DCA	Damage Control Assistant
DIM	Daily Intention Messages
DDG	Destroyer

DOD	Department of Defense
DoF	Degrees of Freedom
DON	Department of the Navy
DTG	Date Time Group
EDO	Engineering Duty Officer
EOOW	Engineer Officers of the Watch
FOV	Field of View
FPS	Frames per Second
GMT	Greenwich Mean Time
GUI	Graphic User Interface
HMD	Head-Mounted Display
HUD	Heads-up Display
IP	Internet Protocol
IP	Information Professional
IRB	Institutional Review Board
IT	Information Technology
JSON	JavaScript Object Notation
MOVES	Modeling Virtual Environments and Simulation
MR	Mixed Reality
MRT	Media Richness Theory
MRTK	Mixed Reality Toolkit
MUVE	Multi-User Virtual Environment
NETOPS	Network Operations
NPS	Naval Graduate School
OPCON	Operational Control
OPORD	Operational Order
OPREP-3	Operational Report-3
OPS	Operations Officer
OT	Operational Technology
PAE	Persistent Augmented Environment
POV	Point of View
PUN	Photon Unity Networking
U.S.	United States
SA	Situational Awareness
SME	Subject Matter Expert

SSQ	Simulator Sickness Questionnaire
SUS	System Usability Scale
SUW	Surface Warfare
SWO	Surface Warfare Officer
TACON	Tactical Control
TASKORD	Tasking Order
WIM	Weekly Intentions Message
VE	Virtual Environment
VR	Virtual Reality
VS	Visual Studio

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I. INTRODUCTION

A. RESEARCH DOMAIN

A persistent augmented environment (PAE) is a system that uses the concepts of shared (multi-user) environments, augmented reality (AR) technology, and a range of sensors to create a visual representation of the processes and data sets that are persistently (over a prolonged period) added, manipulated, visualized, and analyzed to support a range of tasks done by the human operators [1]. PAE is seen as having the potential to bring benefits to many domains and human tasks, including the domain of cyber systems visualization, network situational awareness, and decision-making efforts.

The important concept of PAE includes real-time information delivered to the human operators and in a format that is easier to understand than traditional forms of information recording and delivery. The latter raises the potential to address the needs of many users in diverse communities across the naval domain, reduce the number of errors and dedicate most of the time to the decision-making process.

Because of the large number of users and the diverse communities, the need to collect, process, and manipulate large volumes of data must be addressed accurately and timely. In addition, the complexity of the cyber domain drives the need for simplified, accurate, and timely information. Much like AR systems, the PAE allows users to process and manipulate virtual objects in the real world and simultaneously see automatically synced changes of the system in real-time between a multitude of users. This seamless integration of virtual and real information in real-time addresses the complexity of the cyber domain, ultimately providing accuracy and timeliness of actions between large numbers of users and diverse communities.

We designed and developed a PAE system prototype and analyzed how it can support cyber systems visualization and mission planning operations in the naval domain. The primary goal of our effort is to enhance single-user comprehension and situational awareness about complex cyber networks onboard surface assets and a real-time representation of current network statuses of equipment, thus making Department of the

Navy (DON) mission planning more effective. At the tactical level, this research will further our understanding of the technological infrastructure and processes that need to be established to support effective mission planning. The system has the potential to bring notable benefits to all DOD services.

B. RESEARCH PROBLEM AND MOTIVATION

In the United States Navy, to complete different missions, multiple warfare communities rely on the cyber community to display network and communication statuses to maintain an operational picture and provide communications. The integration of network and combat systems onboard a U.S. surface ship can create confusion among warfighters when displaying information and network statuses as two-dimensional (2D) objects. That is especially the case when unexpected changes occur to network equipment (i.e., loss of power, denial of services, loss of satellite coverage, etc.). Changes to equipment not only impact communication onboard but also affect overall situational awareness among leaders. The integration of three-dimensional (3D) data and stereoscopic display utilizing a PAE system has the potential to significantly assist decision-makers in their understanding of complex networks by automatically displaying system changes in real-time.

1. Cyber Network Is Crucial For Communications (Why We Care)

Cyber networks are crucial for communication between naval assets at the operational level. Without the cyber network equipment, a single surface ship loses the ability to communicate to its chain of command (CoC) quickly and accurately. Likewise, the CoC cannot effectively communicate their information to the individual surface ship. Now, one could take the idea of a single ship without the ability to receive tasking or send status updates and then increase the number of available surface assets into a multiple asset Carrier Strike Group (CSG). This results in five to six ships in an entire CSG without the ability to communicate with the CSG Commander on the current mission or even daily operations. Even though the Navy can use traditional communications, such as morse code and flag signals to relay simple information, more complex information must be represented in an easily digestible format so that the decision-makers can understand current operations and make optimal decisions quickly.

By utilizing a PAE system between surface assets, the PAE system has the potential to improve the understanding of complex information by translating 2D information taken from paper manuals or electronic libraries into a 3D visualization system and constantly updating the 3D visualization to reflect user interaction and constant updates of data sets that system receives and generates. The PAE system also has the potential to access historical data that could be crucial in analyzing historical trends or after-action reports (AAR). Ultimately, the domain of cyber networks is worthy of engaging novel technology and looking for better solutions.

2. Cyber Network Equipment Status

To understand cyber network equipment statuses at the unit level, decision-makers at the strategic level rely on current naval practices that traditionally use briefs, chat, and voice reports. However, that information can be outdated and inaccurate, ultimately creating confusion among decision-makers who need to understand service and equipment availability in the cyber domain. The cyber domain is a complex domain that requires effective management and understanding of network operations, including a shared situational awareness (SA) among the naval Fleet. Network equipment is constantly changing depending on the state of the equipment and the geographical location of a surface ship that can impact connectivity.

Navy operators and leaders traditionally use 2D network topologies and Microsoft files in various formats to depict the operational status of a network system and maintain resource management. These 2D models were originally designed to assist leaders and operators with a clear visualization of the network; however, over time, there has been an increase in network assets and thus an increase in complexity of 2D models, making it much harder to understand these integrated systems. Because of that, the display of 2D network diagrams and topologies has become more of a hindrance to understanding the new system integration or system changes. The amount of time it takes to understand traditional, printed 2D information (Figure 1) does not meet the needs of operators and warfighters anymore, nor does it provide concise and clear information to decision-makers in a timely manner.

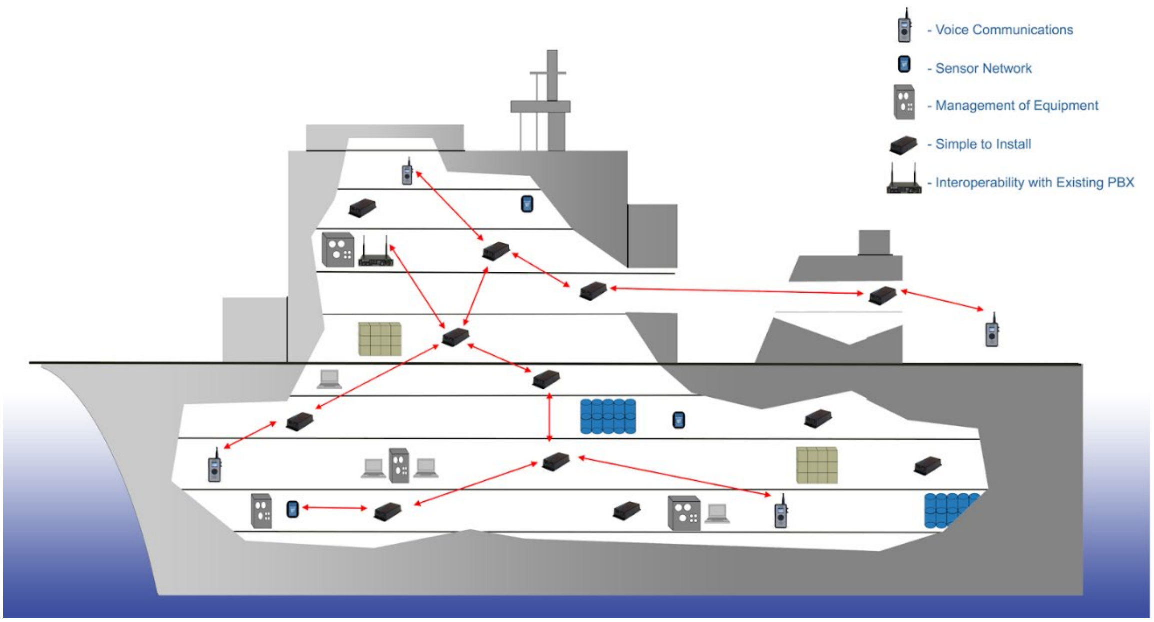

Figure 1. 2D representation of communication suite. Source: [2].

3. PowerPoint Slide (2D Information) to Augmented Reality (3D Information)

Contemporary technologies supporting human operation and decision-making have advanced exponentially from their modest past forms. The representation of data can now take the shape of 3D information that is no longer static but dynamically changing and supporting real-time user interaction with the same data sets. However, the vital communications on most surface assets today include internet connections at different clearance levels that facilitate sharing PowerPoint briefs and receiving voice or written reports represented in 2D space. These traditional avenues of communication are snapshots of a ship's current operational status or set of expectations for upcoming missions; they drive the U.S. Navy's ability to "maintain, train and equip combat-ready naval forces capable of winning wars, deterring aggression and maintaining freedom of the seas" [3]. As recognized in Timmerman's thesis study [4], current 2D visualizations oversimplify complex operational technology (OT) systems by displaying them as the flat information technology (IT) diagrams the networking community is accustomed to seeing. An alternative, more superior representation would be to display logical networking elements in the 3D space that reflects both the physical and logical complexity of these networks. By researching the 3D representation of data, the Navy can expedite the flow of crucial time-sensitive data that was originally in 2D space into easier-to-understand 3D information.

The overarching goal of the research is to provide a quantitative assessment of a PAE system prototype to analyze how it can support cyber system visualization and mission planning operation in the naval domain through a usability study. The traditional understanding of complex cyber networks and their corresponding topology is based on 2D drawings of blueprints that reside in technical manuals. This translation of information is then further diluted by non-subject matter experts (SME) via PowerPoint briefs (or verbal briefs) in order to inform the chain of command at higher levels of decision-makers what the status is of current communications onboard a surface asset. Ultimately, there is a loss of time between 2D information, verbal or PowerPoint briefs, and the delivery of the consolidated information to higher-level decision-makers. The solution to presenting complex systems to decision-makers is representing the 2D information into 3D information via a PAE.

C. RESEARCH QUESTIONS

The thesis addressed the following questions:

- What is the technological framework that has the potential to provide more efficient support for mission planning?
- Can the 3D visualization of network communication capabilities and PAE system provide efficient support for elements of mission planning specific to the cyber domain?
- Can the PAE system effectively assist mission planning tasks at the tactical level specific to the management of network communications?

D. SCOPE

This thesis will be limited to developing a PAE system prototype that will help visualize the cyber infrastructure needed for the user study. The usability study has two distinct purposes: to examine a user's comprehension of 3D visualization of the naval cyber battlespace across multiple ships' communications and network infrastructures and to evaluate the PAE's ability to assist mission planning at the tactical level effectively. While the larger concept of PAE in the Naval domain is envisioned to support many operational tasks and training situations [1], and include interconnectivity with operational systems, the prototype system developed for this thesis will have sufficient functionality to support user study only.

E. METHODOLOGY

The research methodology for this study includes the following steps:

1. **Conduct literature review.** Perform a literature review in the fields of AR, virtual reality (VR), SA, potential multi-user environments, cyber network visualization practices, and persistent systems when applied to AR.

2. **Execute task analysis.** Conduct a task analysis and analyze current practices for cyber network operations, decision-making, and resource management of equipment and service availability across the Fleet. That includes, but is not limited to, detailed analysis of reporting and interactions between Battle Watch Captains (BWC) onboard Carriers with warfare commanders onboard Cruisers or Destroyers (CRUDES), current network visualization practices, and the effectiveness of a PAE. We will also conduct a detailed task analysis of current reporting criteria and existing SA tasks and practices.

3. **Identify 3D models.** Identify a set of 3D models needed to support a virtual environment and user tasks required for the usability study.

4. **Design and develop a PAE prototype.** Design and develop a PAE system prototype that supports the usability study.

5. **Design and execute usability study.** Design a usability study, develop Institutional Review Board (IRB) documentation, conduct a study with human participants, and examine a user's experience performing required tasks. The usability study design will be tailored toward Cyber Domain Visualization, focusing on a user's ability to understand better how network equipment interconnects to other systems and depict the cyber battlespace in real-time. In addition, the design will be tailored to demonstrate decision-making for multi-ship situations and measure the effectiveness of the interface in support of mission planning and resource management.

6. **Analyze data.** Analyze human performance data collected in the study and examine the technical performance of the PAE prototype system.

7. **Identify recommendations and future work.** Collect and identify recommendations for potential future work.

F. THESIS STRUCTURE

Chapter I: Introduction. This chapter introduces the most critical elements of the research space: domain, problem, research questions, scope, and methodology used to address all research questions.

Chapter II: Background and Literature Review. This chapter highlights the definitions of VR, AR, mixed reality (MR), persistent systems, and SA. The text reviews the experiences from research studies that focused on AR and VR technology, and discusses the potential that multi-user environments, existing cyber network visualization practices and persistent systems bring when applied in conjunction with the AR technology.

Chapter III: Task Analysis. This chapter analyzes the current practices for cyber network operations, decision-making, and resource management of equipment and service availability across the Fleet.

Chapter IV: System Prototype. This chapter elaborates on the design and development of a PAE system, the system architecture, and the simulation environment. This chapter also describes the training scenario and a set of 3D models needed to support building a virtual environment required for a usability study.

Chapter V: Usability Study. This chapter presents the elements of a usability study, The text also discusses the results derived from the data sets collected in the usability study.

Chapter VI: Conclusion and Future Work. This chapter outlines the main points from this study and provides suggestions for future work.

II. BACKGROUND AND LITERATURE REVIEW

A. INTRODUCTION

This chapter introduces key concepts and literature review focused on topics relevant to the research domain in the purview of our thesis. That includes the topics of visualization of the cyber network (also known as the cyber battlespace) across the naval domain and the broad concepts required to understand multi-user environments facilitated by data visualization, its impact on collaboration, and decision-making in mission planning. These topics include AR, VR, MR, persistent systems, and SA.

B. AUGMENTED REALITY

1. AR Definition

The most common definition of AR widely accepted in the research community, is Ron Azuma's 1997 [5] definition, where AR is introduced as a variation of Virtual Environments (VE), or VR. While VR immerses a user into an entirely synthetically created environment where the user cannot differentiate any real world or physical entities, AR is the opposite where the user can still differentiate real world or physical entities, like a desk or person, while at the time visually seeing digital virtual objects on top of the real world [5]. In other words, Azuma states that "AR supplements reality, rather than completely replacing it" [5]. Additionally, Azuma states there are three characteristics that distinguish an AR system: they combine real and virtual, support interaction in real-time, and register virtual elements in 3D.

Another definition that complements Azuma's definition is Pettijohn et al. [6]. who states that "AR refers to a display that blends computer-generated and real-world elements to create a hybrid environment, which in this case, may be referred to as augmented virtuality" [7].

By understanding the importance of combining real and virtual information in real-time, AR can enhance a user's perception of and interaction with real and virtual (simulated) information when performing tasks in both the real and virtual (simulated) world. By adding virtual objects and allowing the user to manipulate them freely in the context of the larger augmented environment and functions it supports, users' understanding of a specific task and their subsequent performance can sometimes be significantly improved. For example, if a task is to go from point A to point B, adding a virtual (simulated) map overlay to help a user navigate to point B safely could be useful for the user to save time. Another example would be if a task is to reimagine a floor plan of a potential new house by "removing" certain walls that exist in the real world to create an open floor plan (overlaying the visual information that corresponds to those walls with synthetic information), a user can better understand the space when building a new house and adjusting the design accordingly.

Kipper [8] specifically talks about the two types of AR, where the first is the augmented perception of reality while the second type is the creation of an artificial environment. The first type is practical, showing reality and enhancing what the user can see and/or do, while the second is imaginary showing things that are not real. Regarding the augmented perception of reality, Kipper uses Webster's Dictionary to define the word perception, which is the awareness created by a physical sensation that in turn creates a mental image of what is being received from the eyes to the mind. AR is meant to enhance what a user perceives through their eyes within their surrounding environment both with real and simulated subjects ultimately supporting the decision-making process. By augmenting the perception of reality, more useful information via data visualization overlays the physical world, as seen in Figure 2, which allows for a better understanding of a user's surroundings while improving their decisions and actions.

Figure 2. An example of an augmented perception of reality where relevant information is displayed to aid in decision-making. Source: [8].

By adding the elements of a virtual (simulated) environment, AR allows the user to see things that do not exist in the physical world. An example is a scene from the *Star Wars*-themed game in Figure 3. The elements of the physical environment can be seen in the background, and the virtual environment of *Star Wars* is superimposed on the top.

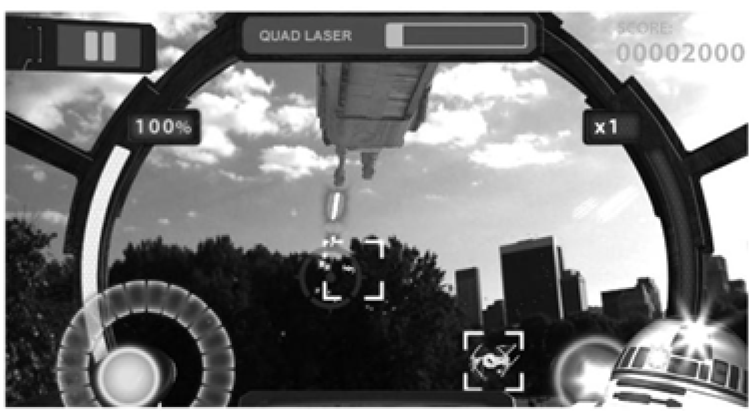

Figure 3. The impossible reality is often used for augmented reality games. In this example, *Star Wars* is the theme for this space combat game. Source: [5].

2. Visual Displays for AR

a. Reality-Virtually Continuum

To understand visual displays for AR, we must first understand the concept of a virtual continuum and the taxonomy or spectrum of visual displays. As seen in Figure 4, Milgram and Kishino's reality-virtuality continuum [7] categorizes or classifies users' mixed reality experiences to include AR and VR. The real environment represents the left side of the diagram – that is all that users experience. Moving to the right, virtual (simulated) information is added to the mix as AR, where virtual objects get superimposed on top of the information that corresponds to the real environment. The right side of the diagram represents a virtual environment that consists of virtual objects that completely immerse the user and replace all information that corresponds to the real world. As a result, a MR environment is between the real world and virtual world, resulting in both real and virtual objects projected onto a single display.

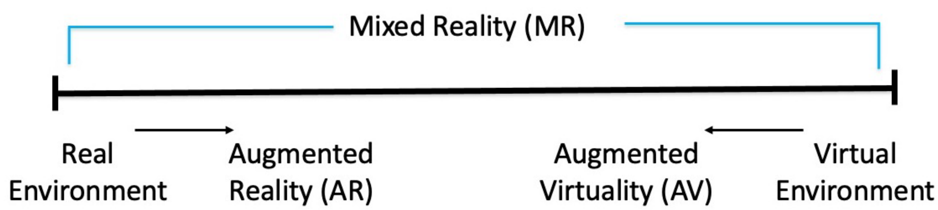

Figure 4. Milgram and Kishino's reality-virtuality continuum. Source:[7].

A variety of visual display solutions are used to support AR user experiences. Bimber and Rashkar elaborate on that topic, and they point out that "Augmented Reality displays are image forming systems that use a set of optical, electronic, and mechanical components to generate images somewhere on the optical path in between the observer's eyes and the physical object to be augmented" [9]. Display Taxonomy shown in Figure 5 includes projections onto the real-world objects, spatial see-through displays, hand-held displays, head-mounted displays (HMDs), and retinal displays. A basic design decision in building an AR system is how and where to combine real and virtual elements of the resulting environment.

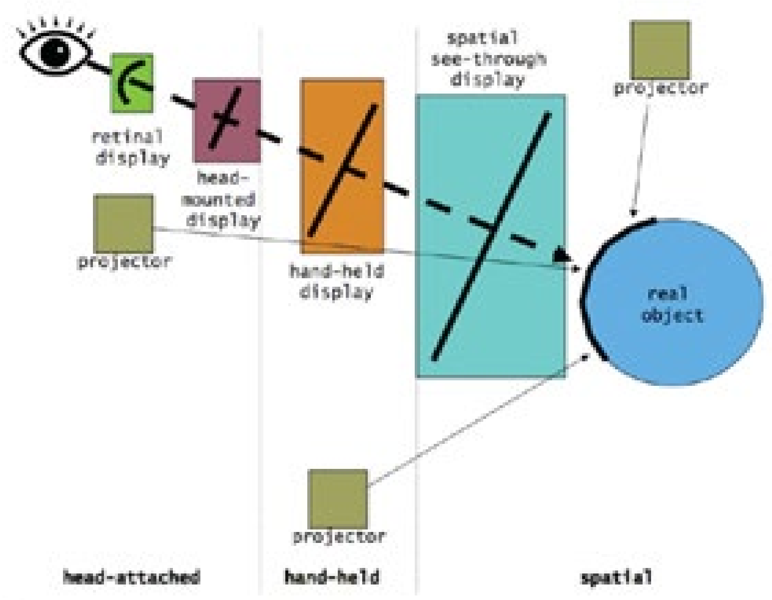

Figure 5. Display taxonomy. Source: [9].

Our work focuses on mobile visual display solutions that allow users hands-free operation, i.e., if needed, they can use their hands to regain balance and navigate around the platform that is moving, like a ship. Those requirements allow for HMD AR displays. There are two approaches used for that type of visual display: optical see-through and video see-through HMD AR display [10]. An optical see-through HMD usually has a see-through visor connected to the headset that allows a user to see both physical real-world objects and corresponding virtual objects that are superimposed onto the real-world pace by technologies that focus on optical or video information. A video-see-through captures visual information about the real world through two cameras (one for each eye), combines it with virtual elements of the environment, and presents it to the user via a display that is similar if not identical to VR HMD.

Optical see-through HMDs use partially transmissive optical combiners in front of the user's eyes through the see-through visor connected to the headset. This directly focuses the users' eyes to see the real world normally but also the combiner as well that project the 3D digital information. These combiners are partially reflective as well that bounce off the virtual images between the users eyes and the combiners similarly to the nature of a Head-Up Displays (HUDs) most commonly used in military aircraft. However, the HMD is attached to the head unlike the HUD which is attached to the console in front of the pilot's eyes thus optical see-through HMDs can also be referred to as a "HUD on a head" [1]. Hughes Electronics shows the concept of an optical see-through HMD in Figure 6.

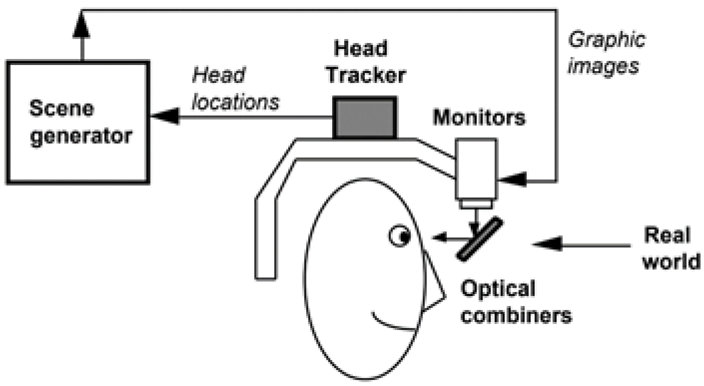

Figure 6. Optical see-through HMD conceptual diagram. Source: [5].

3. Cybersickness

Cybersickness is typically associated with VR systems; however, recent research done by Timmerman [4], [11] suggests that even AR users can experience some symptoms of cybersickness. Most specifically, the user study with AR headsets registered heightened oculomotor symptoms.

a. Sickness Definitions

Cyber sickness is defined as "visually induced motion sickness" [12]. Typically, a user is immobile when immersed into VR, however, when there is motion presented through visual imagery, a user can have a sense of motion [12]. For example, VR applications tend to limit the user's movement to a singular area of space, and the user navigates through 3D space by pressing the button on the hand controller. This conflict of vestibular and visual sensory stimuli is seen as causing the symptoms of cybersickness.

Motion sickness is defined as "sickness induced by motion" where there is a mix-match of information between a user's visuo-vestibular system and the visual information they are receiving through their eyes that can cause motion sickness [13]. Common examples include seasickness, car sickness, airsickness, and space sickness.

Simulator sickness is defined as "symptoms related to the combination of motion and either VR or AR" [6]. The military uses simulators to train personnel to drive naval vessels, fly aircraft, and drive land vehicles. Thus, the military instructions define simulator sickness as "the experience of symptoms such as nausea, disorientation, and sweating has occurred in fighter, attack, patrol, and helicopter simulators." Below are two examples of military instruction specifically created to regulate and minimize simulator sickness:

- The U.S. Coast Guard's *Air Operations Manual*: COMDTINST M3710.1H (26 Oct 2018)— "Simulator, Aircrew Weapons Trainer (AWT) and Cockpit Procedures Trainer events may be scheduled any time after aircraft events… aircraft events are not authorized within the 12-hour period immediately after simulator or AWT events. An event is defined as any time spent in the simulator with visuals or motion turned on" [14].

- The Navy's *COMNAVAIRFOR Manual* 3710.7 N45 8.3.2.16 Simulator Sickness (2 May 2016)- "Symptoms of simulator sickness may occur during simulator flight and last several hours after exposure. In some cases the onset of symptoms has been delayed as much as 18 hours... Flight personnel exhibiting symptoms of simulator sickness should consult with a Flight Surgeon prior to returning to flight duties" [15].

It is important to acknowledge that future instructions regarding the use of VR and AR technology get updated to also include mobile platforms.

b. Symptoms of Cybersickness

Stanney and Dexler found that cybersickness is not the same as simulator sickness because there is differing symptomatology where "users of VE systems are more prone to experience dizziness, vertigo, general discomfort, increased salivation, sweating, and nausea than they are to encounter the headaches, eyestrain, or difficulty focusing frequently experienced by users of simulator systems" [16].

In two recent NPS theses, researchers demonstrated symptom distinction between AR and VR systems. For AR HMD in Timmerman's thesis, subjects reported higher discomfort associated with oculomotor symptoms, like dizziness and vertigo while standing and interacting with the AR environment [4]. For VR HMD in Yamashita's thesis, subjects reported more eye strain, difficulty focusing, and blurred vision while sitting and interacting with the virtual environment used to support assembly tasks [17].

AR device can be utilized both on stationary (land base) and on the platforms that are in motion (Navy surface asset or ship). Pettijohn's research specifically involves studying how physical motion affects user symptoms through motion conditions to simulate or mimic the realistic motion of a U.S. Arleigh-Burke class destroyer underway in calm seas and firing hostile ships [6]. This is a relevant study because "motion-based scenarios are important for military applications because most military-relevant scenarios replicated with mixed reality are likely to have real-world corollaries that involve physical motion" [6]. Specifically looking at a training scenario where a ship is out to sea, there is natural motion from the ocean waves that can be affected by weather, ship type, and sea state. With this natural motion to consider, the study focused testing under three motion conditions with both VR and AR: the first being "No Physical Motion" where it was a stable physical environment, the second being "Synchronous Motion" where it was physical motion, and its matching displayed motion, and finally "Asynchronous Motion" where physical motion did not match the displayed motion.

The results of Pettijohn's research [6] showed that sickness symptoms generally increased over time regardless of the form of the headset - VR or AR. The distinction between VR and AR could not be concluded based on the short timeframe of the study, but it can be concluded that the combination of VR or AR technology with a synchronous motion profile was sufficient to induce simulator sickness [6]. However, there is a possibility that if a user is exposed to the simulator for a longer period of time or that the simulator exposure has more rigorous motion, it can result in differences between both systems. Overall, this study demonstrated that the gentler motion conditions can be considered normal conditions that positively show that VR or AR can be deployed for the purpose of training [6].

C. PERSISTENT SYSTEMS

1. Definitions and Concepts

As of 2021, a “persistent system” is not explicitly defined. However, according to Webster’s Dictionary, “persistent” is defined as “existing for a long or longer than usual time or continuously “ [18]. In the case of the persistent virtual environment, for example, those would be VEs that are always ‘up and running.’ A typical example is Second Life, a multi-user virtual environment that is always operational; users log in and log out; however, the environment and activities in it are always available to others who inhabit it [19].

Liskov et al. used the term “persistent object” [20]. They state that “a persistent decouples the object model from individual programs, effectively providing a persistent heap that can be shared by many different programs: objects in the heap survive and can be used by applications so long as they can be referenced” [20]. With this in mind, it can be implied that a persistent system can continuously and consistently store and retrieve different objects regardless of time and space as long as the object can be referenced. This suggests that a user can save information as an object, step away for hours or days, come back, retrieve the saved information of that object, continue using the object for whatever reason (manipulate the data in some way), and access this information from another platform regardless of physical location.

Furthermore, Liskov et al. [20]. concluded that future use of persistent objects can improve vital changes in computer architectures, distribution applications, and systems for supporting persistence. Specifically between file systems and constantly growing applications, the fast-paced increase of technology creates a gap in data safety as well as performance. By having a “persistent object storage system,” the ability to save, access, and manipulate objects continuously can enhance data safety and higher performance.

2. Pervasive Augmented Reality, Persistent Systems and Persistent Augmented Environments

Originally, we talked about Liskov et al. work from 1996 research to understand the importance of a potential “persistent object storage system,” coincidently, Liskov conducts research studies based two [20],[21] of his studies to further explain the importance of a persistent system as an application:

In Liskov et al. 1996 “Safe and Efficient Sharing of Persistent Objects in Thor” [20], more research was done demonstrating the safety and efficiency that persistent systems, specifically the system named Thor, can have. Thor, an object-oriented database system, was designed to be implemented by heterogeneous distributed systems providing highly reliable and highly available storage. Highly reliable storage includes object sharing within different levels of the operating system of the machine, the machine itself, the network the machine is running on, and the programming language used by the machine with a strong safety guarantee that “objects can be used only according to their types” which is a huge benefit of data abstraction. Highly available storage includes the ease of sharing objects between different applications, or components of the same application as well as the integrity of storage despite failures.

In Liskov et al. 1999 “Providing Persistent Objects in Distributed Systems” [21], Liskov further explains Thor’s safety for sharing objects across space and time while still achieving high performance. Fast forward to 2021, we have now created persistent systems without defining that they are persistent systems. Easy examples are like on social media through the power of the internet.

A specific example of a persistent system can be seen through Microsoft’s OneDrive. For example, Microsoft “How OneDrive Sync Works” demonstrates how a single Microsoft Word document saved onto a person’s personal computer can be simultaneously saved onto Microsoft OneDrive. Specifically OneDrive communicates with individual Office apps to trade metadata about changes so that syncing is done correctly [22]. Also, collaborative syncing can be treated as an “object” in which this “object” is saved to OneDrive. This is important since everyone in the world today relies on constantly updating information for convenience and for safety. Like when a Word document can recall “last saved information” (time and date) of a person’s document to be able to see the last thing they were doing on their document. A person can also see edits of what another person was doing if that feature was enabled.

Technically speaking, the entire Microsoft Word document itself can be considered an object that is being stored in a system that automatically updates and syncs regardless of if a person is using the document or not. For example, a person can be away from the document but the data it is stored in Microsoft word servers (like OneDrive), or their local computer is still running so when the person comes back, the last version can be pulled safely. Again, tying it back to Liskov et al. "Providing persistent Object in distributed Data" [21], the word document as an object contains data stored as a heap in the persistent system thus is easily translated to be shared on different platforms, for example: word document in google docs or save as a pdf or a txt file, as long as they are referenced or called upon to be manipulated. In other words, sharing objects between both time and space since Liskov says that "objects can be used concurrently by applications running at the same time but at different locations: different processors within a multiprocessor; or different processors within a distributed environment."

Grubert et al. introduced the term Pervasive Augmented Reality; they define "Pervasive Augmented Reality as a continuous, omnipresent, and universal augmented interface to information in the physical world… we define Pervasive Augmented Reality as a continuous and pervasive user interface that augments the physical world with digital information registered in 3D while being aware of and responsive to the user's context" [23]. The authors proposed the taxonomy for Pervasive Augmented Reality, context-aware Augmented Reality, and outlined the domains that will need to be addressed to fully realize this type of technology.

In an internal report of an NPS document by Dr. Amela Sadagic [1], a Persistent Augmented Environment (PAE) is defined as a system that uses the concepts of shared (multi-user) environments, augmented reality (AR) technology, and a range of sensors to create a visual representation of the desired content that is persistently (over a prolonged period) added, manipulated, visualized, and analyzed to support a range of tasks done by the human operators. This type of system technology has been proposed as a novel form of communication platform in support of daily operations onboard Navy ships and installations; this type of system would have major impacts on DON operational readiness while providing strategic advantage for augmentation of human operations [1].

The research efforts done by Guo et al. focused on the objects persisting in physical space in a collaborative AR environment between a single-user or multiple users to understand to promote the effectiveness collaborative AR experiences can bring [24]. Building blocks were a simplistic approach to evaluate how participants interacted between space and time as the two specific collaborative dimensions to support understanding collaboration [24]. The research created structures synchronously with collocated collaborators. It is important to note Guo et al. study was not restricted by time or place. That particular approach is important to the research conducted in our thesis, as PAEs are imagined not to be limited to space or time.

Guo et al. outlines in his study that there are new design opportunities that both persistent and collaborative AR experiences can have to eventually empower anyone around the world to collaborate and create their own AR content specific to their needs. This is very different from today's current AR experiences that only focus on consuming content rather than focusing on collaborating for a purpose [24]. The blocks created by participants are created in a persistent AR structure to ensure each session created by multiple participants is tied to the physical location and that a particular user created blocks, or the structures are stored and shared in a location-independent environment. As Guo et al. discussed the collaborative and persistent augmented reality experiences within his application, there were two locations of AR structures: dependent and independent. In addition, they evaluated participants in two locations, collocated and remote. Essentially, a location-independent environment consists of the block structures stored in a shared AR environment, while a location-dependent environment houses the block structures tied to the user's physical location.

Pan et al.[25] specifically studied collaboration modalities by homing in on different mixed reality settings between multiple users to understand effective synchronous collaboration. He found that greater collaboration, embodiment, presence, and co-presence were related to AR-to-AR collaboration [24]. The key to a successful collaborative AR environment is the feedback provided by participants. Since the focus of Guo et al. [24]. application was collaboration, the experiment involved participants expressing their interaction with the system as they actively used the environment to assist builders with refining the design of the blocks. Google Docs inspired the block application to provide users collaborative tools whether they are in a co-located or remote setting. The study's purpose was to understand the overall benefits that different collaborative AR experiences can bring utilizing a single application but specifying three particular modes within a persistent environment seen in Figure 7 [24].

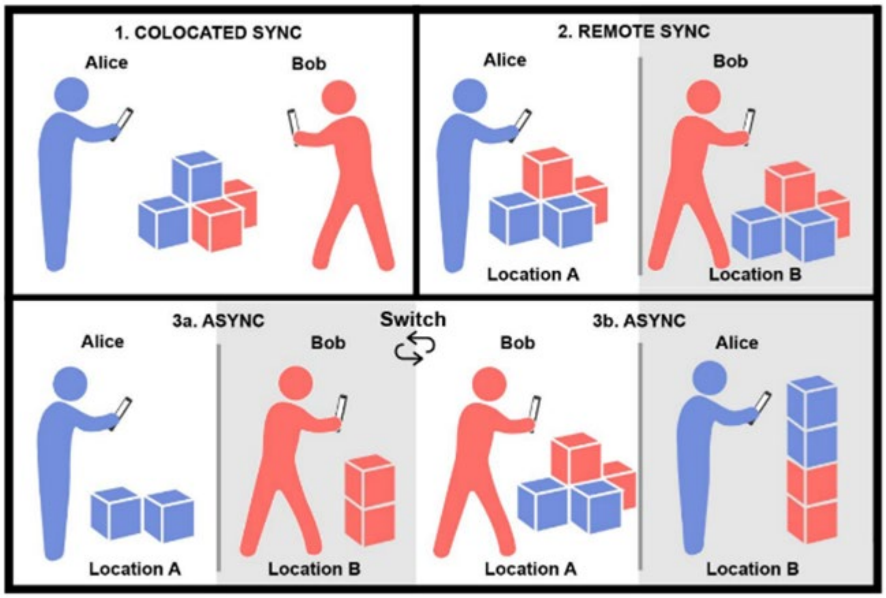

Figure 7. Guo's experimental setup for lab study. 1 is a co-located-sync condition, 2 is a remote-sync condition, and 3a and b is an async condition. Source: [23].

The results of Guo et al. [24]. study showed that collaboration between participants was successfully achieved; however, co-location of participants enabled better communication and collaboration. In addition, participants were able to move in the physical space easily and walked less in a collocated environment. The only drawback of the application was that permission controls had to be addressed to determine if participants would like their work modified by others operating in a persistent environment.

Even though participants had access to the application to promote collaboration, participants planned tasks before creating blocks, which is expected if one wants to achieve effective planning. Designers have to account for out-of-sight objects that users may not see to provide the perception of other users in an AR environment even though they may not see them in a co-location environment. The application used in Guo et al. [24]. study was a great tool that used AR and persistent systems to allow users the ability to manipulate virtual objects regardless of their physical location and allow information to be accessible to others for effective communication and collaboration.

We define a *persistent system* as a group of devices or artificial objects forming a continuously existing network to serve a common purpose. We propose this definition after our study of AR persistent systems by Guo et al. [24], Huntley [26] work on persistent AR, and the research done by Billinghurst et al. [27]. focused on collaborative computing.

Huntley's research [26] laid out the groundwork on the importance of using mobile AR devices on the Navy surface vessels. Huntley emphasized the safety required for the collaboration of multiple operators on the same ship. By applying AR display technology in a persistent environment (and not using VR displays, for example), human operators can safely traverse the physical space, especially onboard a moving ship. Safety is the number one priority onboard a ship and keeping a user safe onboard a moving vessel. That can be better achieved by using AR displays that allow the user to clearly see the elements of physical environment and maintain situational awareness, while also having the immediate access to a virtual element of persistent environment. By using mobile AR displays the operators were able to enhance their decision-making no matter where they were on the ship. He emphasized that human operators must have the ability to interact with other users, the ship, other systems, and maintain constant awareness of their surroundings [26].

Huntley's research examined how the persistent use of augmented reality could improve situational awareness and have a positive effect on decision-making by enabling more timely decisions or better decisions overall [26]. The results from his usability study revealed users' ability to make decisions positively improved when using the AR display; the up-to-date knowledge, prompt reporting, and the ability to multitask between different mission areas onboard a surface vessel was seen as being crucial augmentations of the operations conducted by naval personnel.

Billinghurst et al. introduced the concept of "collaborative computing"; the observed capabilities of the technology and the increase of remote communication still limited computer-supported face-to-face interaction and communication between remote users (i.e. Zoom for video conferencing) [27], [28]. A real-time collaboration between multiple users can be facilitated using live video feeds presented on a screen, however, there are still limitations associated with 2D representations of information like PowerPoint or other shared documents. Additionally, when there is collaboration in the real-world, multiple users can see both the real physical objects and the digital information simultaneously to manipulate the same objects through face-to face interaction but also through remote locations. Billinghurst et al. [27]. introduced the concept of "Shared Space" that uses AR to simulate the same freedom and flexibility of interaction as real-world collaboration. The goal was to improve two specific types of interactions where the first was between humans and computers while the second was between humans mediated by computer-generate imagery. This "Shared Space" concept investigated the effectiveness of developing a collaborative AR experience by improving the user interface within both physical and spatial areas.

The concept of Shared Space started answering questions like "How will we interact in such collaborative spaces? How will we interact with each other? What new applications can be developed using this technology?" [27]. Shared Space also allowed users to use items they were already accustomed to within the Shared like physical notes, diagrams, books, and other real objects while simultaneously viewing and interacting with virtual images. This is important because this facilitates multiple users in one location to see each other's facial expressions, gestures, and body language as they would normally do since natural face-to-face communication cues are common and easily understood. The Shared Space interface also had the added benefit where multiple users could be either physically co-located or located in different physical places while still simultaneously working in both the real physical world and the virtual world (Figure 8). This is possible since the shared data comes from a shared database that contains shared virtual objects via the cards with their corresponding tracking markers. Each card has printed marker that is tracked and recognized by the system; once the marker is recognized the system produces a 3D virtual object and situate it above the marker. Each user can see that virtual object from a personal viewpoint and interact with it. Users can pass around physical cards and, in that way, achieve the natural freedom of collaboration. Shared Space therefore gives users the same experience and realistic visual functionality of manipulating shared objects that they would have in the real world.

Figure 8. Users around the playing table (left) and a virtual object on a card (right). Source: [28].

In conclusion, for the purpose of this thesis, we define PAE as a technology that offers users the ability to manipulate AR objects, conduct synchronous and asynchronous interaction, and collaboration with other users while forming a continuously existing network to serve a common purpose.

3. Conclusion

To restate the scope of this paper, this thesis will be limited to developing a prototype PAE to visualize the cyber network infrastructure between multiple ships and examining the usability of the resulting user interface. While the larger concept of PAE in the Naval domain is envisioned to support many operational tasks and training situations, the system developed for this thesis will have functionality sufficient to support user study only. The origin research of persistent systems and their evolution to persistent augmented environments is vital since the fundamentals of communication to support a single task is dependent on reliable, accurate, and time-sensitive data from one person to another. By understanding how communication of information is executed between two people (or entities) in this highly technological and data driven world of the 21st century, the Navy can take advantage of this to support mission planning and execution.

Effective planning involves multiple users having the ability to quickly communicate regardless of their physical location. The use of a persistent system in an AR environment will not only increase communication among leaders, but also allow faster access to the latest information within the Fleet. As for naval mission planning, collaboration is crucial for planning and execution; therefore, immediate feedback of a persistent AR application would be highly beneficial. Immediate feedback from a persistent AR application would assist leaders from multiple communities and operational expertise to seamlessly collaborate and build mission plans.

Persistent systems applied to collaborative tools can be designed and implemented as seen by Lisvok [20] and Guo [24]. Liskov focused on storing information in a reliable and highly accessible manner while also maintaining the integrity of the information, and where Guo focused on the synchronized manipulation of user created virtual objects persistently in the physical environment. Applying both focus areas would allow users to store data in a server, allow multi-users to manipulate virtual objects in their own respective physical environment as well as collaborate synchronously or asynchronously for effective communication and mission planning.

D. MULTI-USER COLLABORATIVE ENVIRONMENTS

1. Definitions

According to Webster's Dictionary, collaboration is defined as "[working] with another person or group in order to achieve or do something" [29]. People continuously find ways to communicate and achieve certain tasks by utilizing current technologies. Today, collaboration via current means include face-to-face interactions with people in the same physical space, or remote interaction with people physically miles away from each other. With the growing need to collaborate with others, people require real-time interaction with others, either locally or remotely. The advent of video conferencing, virtual environments, and augmented environments aid in the ability to collaborate.

According to Goebbels at al., “Collaborative Virtual Environments (CVE) are multi-party Virtual Environments, which allow a number of users to share a common virtual space, where they may interact with each other and the environment itself.” [30] According to Schroeder, a Multi-User Virtual Environment (MUVE) consist of four components:

1. Place & Space
2. Task
3. Interpersonal interaction and communication
4. Changes over time: Short term (initial few minutes) vs. medium term vs. long term [31].

AR technology specifically allows users to view and interact in real-time with virtual images that are superimposed over the real world to then create collaborative experiences and thus is both a CVE and MUVE.

2. Background

Normally people collaborate in a single physical space looking at a table or viewing a screen with 2D information displayed to complete a specific task. For example, Figure 9 demonstrates two people using the table as a task space and thus the room is the communication space where shared communication cues can be witnessed between both parties. Otherwise, video conferencing technology would have to be used to allow multiple people to focus on a single screen with the information like a PowerPoint presentation to talk and collaborate on. Regardless of in person or video interactions, conferencing abilities result in the fundamental need to share communication cues such as gaze (does someone look bored or confused), gestures (emphasizing a point by using hands to point) and non-verbal behaviors (sighing in frustration, rolling of the eyes, crossed arms etc.) [32].

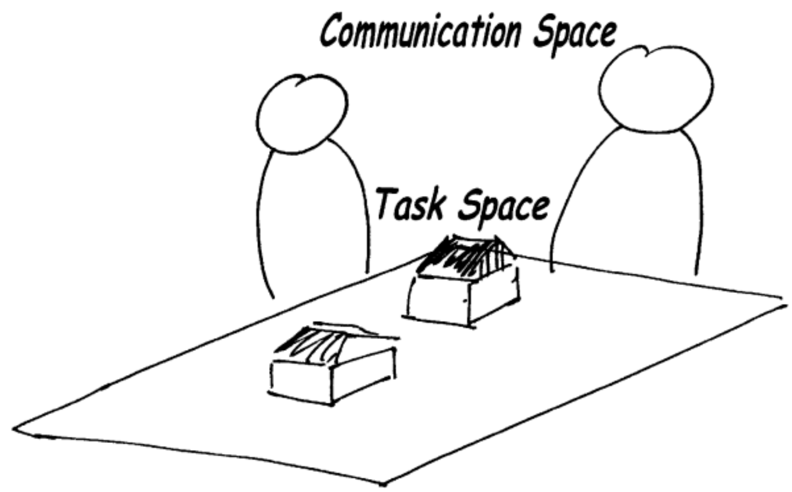

Figure 9. Face-to-face collaboration. Source: [32].

With AR, people can now interact both locally and remotely and see shared 3D virtual objects. The communication space now becomes the augmented environment the users use via their headsets and the task space becomes the virtual objects that all users can interact with simultaneously thus enabling a more collaborative experience even in a remote setting. The ability for remote users to share the same virtual space face-to-face in collaborative AR experiences allows users to feel as if they are co-located virtually since they are given realistic interactions to achieve tasks within this collaborative space [32].

Billinghusrst et al. stated “collaboration in a face-to-face setting with AR technology will produce communication behaviors that are more like those produced during natural face-to-face interaction than when using a screen-based interface” [32]. It was found that human communication behaviors could be measured that were dependent on interface affordances of each condition seen in Table 1. These conditions predict the overall influence these innate characteristics have for a specific condition on communication behaviors. This section will delve into more detail to demonstrate the strengths (and weaknesses) of both face-to-face and remote collaboration via AR.

Table 1. Interface affordances of each condition. Source: [32].

	Face-to-face	Augmented Reality	Projection screen
User viewpoint	Natural eyes Independent view Easy to change viewpoint	Private display Independent view Easy to change viewpoint	Public display Common viewpoint Difficult to change viewpoint
Interaction	Natural object manipulation Two handed Space-multiplexed input	Tangible AR techniques Two handed Space-multiplexed input	Mouse-based One handed Time-multiplexed

3. Face-to-Face (Local) Collaboration

Face-to-Face, local collaboration focuses on the natural face-to-face communication and behaviors like gaze, gestures, and non-verbal cues. Users can use this specific AR interface that combines superimposed virtual objects with real objects to manipulate spatial data as if they were real objects. Several studies have explored the effectiveness of using AR for complex tasks by showing AR can improve the effectiveness of tasks and performance time while reducing the mental effort of tasks to include collaborative design tasks [32]. Examples include the collaborative AR game called Shared Space from the previous section that was originally designed for novices [32]. Another example is AR PRISM which is an AR interface for geospatial visualization [32].

In Lukosch's research "Collaboration in Augmented Reality" there are other examples demonstrating AR technology that support face-to-face collaboration including the Studierstube system that emphasizes an educational environment for users to interact with different educational information and presentations [33], [34]. Another example is EMMIE, which uses AR to visualize cross-device interactions, search, and privacy statuses of users to continuously connect people and their devices during a particular meeting [35].

Additionally, VITA is an AR interface used in a full-scale archeological dig to represent realistic representation of the site to multiple users [36]. VITA also gives multiple users the ability to collaborate with dynamic visual simulations specifically meant for understanding engineering processes while wearing HMDs around a single table [37].

Ultimately, the key lessons that were learned from these systems were that "users can interact with shared AR content as naturally as with physical objects, AR reduces separation between task space and communication space, and that AR enhances natural face-to-face communication cues" [38].

4. Remote Collaboration via AR

Remote collaboration focuses on the fact that users do not have to be located in the same physical space to collaborate, instead the AR interface provides a virtual co-location in order to spatially collaborate with others to create a shared understanding of the information presented. Several studies have explored the effectiveness of using AR for remote collaboration, concluding AR improves the satisfaction with remote collaboration on physical tasks since it supports mutual understanding and leads to group consensus. This includes the ability to use an AR telepointer to guide user focus smartly and easily to a specific activity.

In Lukosch's research "Collaboration in Augmented Reality" other relevant examples of using AR technology to support remote collaboration include WearCom [27] that represent remote collaborators as virtual avatars. Another example is Höllerer et al. [39]. that allows both users found in indoor or outdoor AR environments to visualize each other's respective pathways they traveled as well as their physical locations within the virtual space and have the ability to share annotations. Additionally, Minatani et al. [40]. describes an AR conferencing scenario where the specific system is a tabletop game where multiple users can play simultaneously. Also, Poelman et al. [41]. introduces and evaluates an AR system that uses a virtual crime scene space to facilitate an investigation to secure evidence between both local and remote investigators. Finally, Datcu et al. [42]. presents a system that focuses on the security domain in order to enhance SA between teams across the organization to promote smooth integration.

Ultimately, the key lessons learned from these systems were "AR technology can reproduce some of the spatial cues used in face-to-face collaboration that are normally lost in remote conferencing systems, AR can increase social presence compared to other technologies, and AR also allows remote collaborators to interact naturally in the local user's real environment" [38].

E. SOCIAL PRESENCE

1. Definitions

Social presence can be defined as “the degree to which a medium facilitates awareness of the other person and interpersonal relationships during the interaction” [1]. This means that the awareness between two or more people based on the proximity to each other (either physically or virtually), influences effective interaction between group members in order to perform tasks together. Specifically with decision-making tasks that involve the exchange of verbal and electronic information, these tasks require higher levels of understanding between group members in which social presence can effectively increase. In other words, the collaboration of group members influenced by social presence allows for the sharing of knowledge, ideas, opinions, and information required to accomplish a task.

Earlier in this paper, collaboration was introduced where people share communication cues such as gaze (does someone look bored or confused), gestures (emphasizing a point by using hands to point) and non-verbal behaviors (sighing in frustration, rolling of the eyes, crossed arms etc.) [32]. With that in mind, voice additionally affects the group interaction process since one’s ability to convey their opinions and expertise via voice tends to be the first form of communication within a group. Voicing out ideas and opinions then contributes to individual fears of criticism between group members that can affect decision-making. For example, a common group dynamic could be where one person dominates the conversation and thus the remaining group members believe his or her opinions are the only valid ones. This is important because this is fundamentally what social presence affects when a group of two or more individuals comes together to accomplish a task. In Roberts et al. research, the voice effect is defined as “having the opportunity to provide input on decisions that will enhance judgments of fairness” where these fairness perceptions can produce positive results between groups of people to include higher commitment, increased organization, and better work output [43].

Goebbels et al. research describes the "Collaborative Awareness-Action-Feedback Loop" [30] where the user perceives the co-presence of another individual during the awareness phase shown in Figure 10.

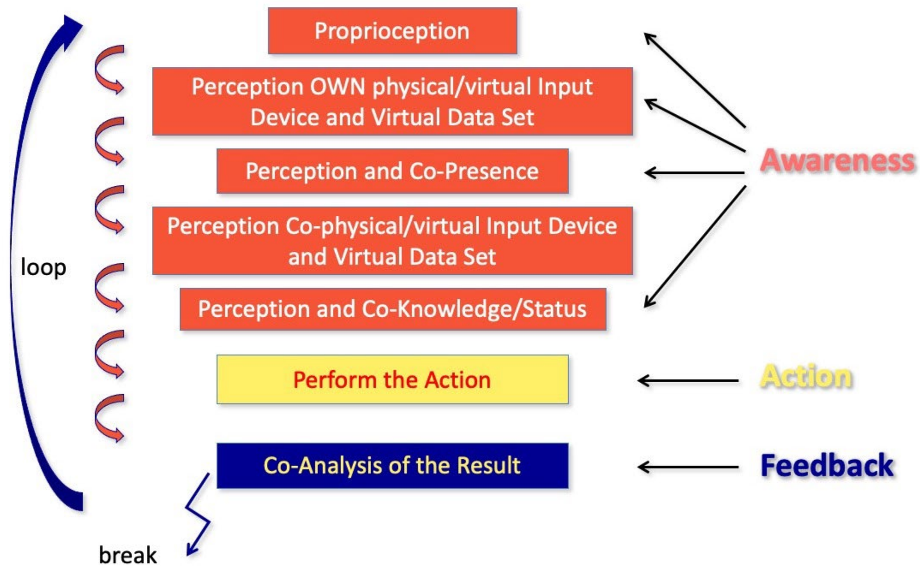

Figure 10. Collaborative awareness-action feedback loop. Source: [30].

This is important because it was found that "knowing that your partner is aware of you is one of the most important steps in this awareness phase" [30]. In other words, a user feels validation (awareness) in this collaborative awareness-action-feedback loop from their partner with a verbal "yes" or a gesture like the "thumbs up" (action) that results in a feeling of accomplishment (feedback). Additionally, in Schmidt et al. study, there was a virtual team that communicated better as a team when asynchronously using groupware technology thus strongly suggested that individuals make less effective decisions compared to a team [44].

Presence in shared VEs is defined as "the extent to which the individual has a sense of belonging to a totality that is more than just the sum of individuals, the extent to which the group as a whole takes on behavior that is not a conscious decision of any particular individual" [45]. This starts to dive into the importance of group size on social presence. Small group sizes tend to facilitate more social presence since every member of the group can comfortably share ideas and voice their opinions. Larger group sizes; however, facilitate social presence less since there are more group members to introduce a complexity in interaction and reciprocity [43].

2. Avatar

The key to productive and effective presence in virtual environments are the interpersonal relationships and the sharing of communication cues. This is highly dependent on the visual representation of the user's body being represented in the virtual environment. This bodily representation of a user is known as their avatar appearance. In Schroeder's research "Comparing Avatar and Video Representations" [31], "the range of avatar representations and representations in video-mediated communication" are discussed to demonstrate that future user representations will differ between being represented using a video-realistic representation versus using a computer-generated representation. The differences between video and avatar forms of representation through video-mediated interactions are seen in Table 2. Mainly, it was found that when using avatar representation, users were not entirely convinced that the representation was real since avatars are clearly "constructed" vice captured real live video. This fundamental difference of "real person" vs "constructed" forces a user to act inherently different. For example, a live video feed induces another person to interact normally, while a live video feed of an avatar encourages another person to pause and hesitate in the beginning before getting used to the avatar.

Table 2. Key characteristics of avatar vs. video mediated interaction. Source: [31].

	Video	Avatar
Representation	True to life	Constructed, but can approach realism
Body capabilities	Limited to physical ones	'Super powers'
Environment apart from person representation	Typically limited to context of head and shoulders, i.e. table and room	From room-size spaces to vast interconnected worlds
Interpersonal interaction	Focus on facial expressions	Focus on spatial encounters with bodies
Number of participants	Two - to small groups	Two - to large populations (though still focused on the group)
Advantage	Few concerns about deception	Plasticity of self-presentation
Disadvantage	Concerns about one's appearance (can be avoided with picture-in-picture)	Inability to come across as oneself

Even though full body representation of avatars has not been fully researched in AR, Miller et al. research "Social Presence Outside the AR Field of View" starts to research this concept by focusing on an AR headsets field of view (FOV) and interaction with avatars. In summary, Miller et al. [46]. study participant's perception of a virtual character that was outside the FOV was less likely to have a high social presence score but did not find a difference in task performance score. Ultimately, "these findings inform application design and encourage future work in theories of AR perception and perception of virtual humans" [46].

F. MISSION PLANNING

1. Mission Planning Definition

According to the Joint Publication 3 [47], the *mission* has several distinct meanings. It can be defined as having a task combined with a clearly defined purpose to take appropriate action within reason. Specifically in lower military units, mission can be assigned to a specific individual or unit to take specific action to achieve the purpose of the task.

Furthermore, a *mission* always consists of five parts [48]:

1. Who (organization to act),
2. What (the task to be accomplished and actions to be taken),
3. When (time to accomplish the task),
4. Where (the location to accomplish the task), and
5. Why (the purpose the task is to support).

For the purpose of this thesis, *mission planning* will be defined as combatant commanders and their subordinate commanders planning specific activities for task driven military operations previously identified [49].

Understanding the five parts of a mission provides commanders the foundation to assess an area of responsibility (AOR) and determine how to use his or her resources to plan out operations. Commanders rely on the guidance of their staff to provide direction and assessment of the commander's capabilities and objectives to define military operations. Additionally, the planning process guides operational units to execute and achieve the desired objective for military operations. For example, a Fleet Commander (the 'who') has an objective to increase presence (the 'what' and 'why') in a specific geographical area (the 'where') and orders his staff to create an operational campaign to fulfill his or her intent by a designated time (the 'when').

As seen in this example, planning involves multiple SME from multiple naval communities and the understanding of resource management and asset availability which fundamentally increases the level of complexity of making decisions. By applying this foundation of a *mission,* multiple entities must collaborate to discuss their assets and resources to achieve the commander's intent.

Successful mission planning requires a team of planners that can collaborate efficiently and have constant access to accurate information in a timely manner; however, a burden has been placed on commanders and planners to remain responsive and adaptive in real-time using current practices.

2. Levels of Mission Planning

There are three levels of warfare (mission planning) in the Department of Defense: strategic, operational, and tactical as shown in Figure 11.

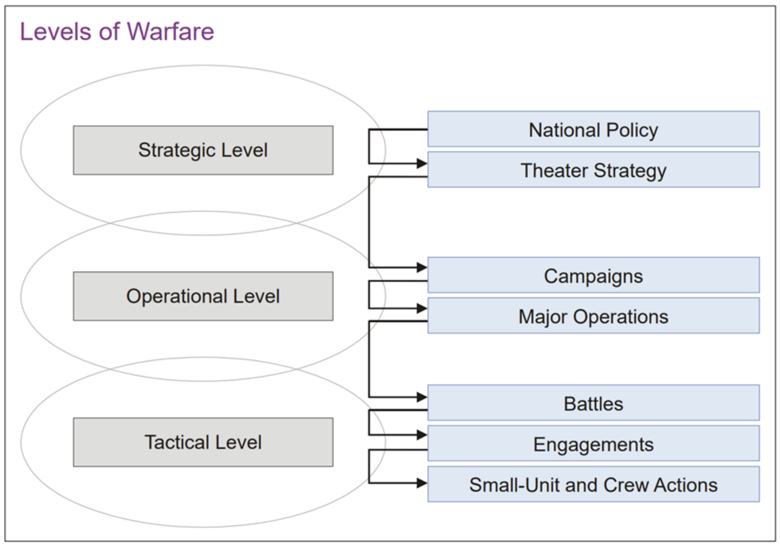

Figure 11. Levels of warfare. Source: [49].

These levels may look to have boundaries between them; however they are flexible to assist decision-makers at all levels to effectively design and synchronize their operations seamlessly, allocate the appropriate resources, and concisely assign tasks to the appropriate commands. The nature of the task, objectives, or mission is required to understand the strategic, operational, or tactical purposes of employing certain resources, but each level of warfare (mission planning) is linked to tactical actions to achieve objectives [48]. In order to achieve strategic end states, the strategic level determines the national guidance to address strategic objectives to develop and use national resources to achieve them [48]. In order to achieve operational end states, the operational level uses operational art to plan and execute operations. Operational art is “the cognitive approach by commanders and staff—supported by their skill, knowledge, experience, creativity, and judgment—to develop strategies, campaigns, and operations to organize and employ military forces by integrating ends, ways, and means” [48]. To achieve, tactical military objectives, the tactical level consists of both battles and engagements specifically assigned to tactical units or Joint Task Forces (JTFs) [48].

For example, a decision-maker at the operational level (usually in the role of commander, not necessarily rank) can have the intent to increase presence in a specific geographical area; thus, his or her objective can only be met by a mission planning team composed of multiple SME from diverse naval communities (cyber, intelligence, navigation, weapons). That is needed to discuss and manage individual assets and resources each particular SME has available to accomplish the commander's intent. In the context of this thesis, we will focus on the tactical level of mission planning. That will consist of a single CSG that is made up of a single Cruiser (CG) and three Destroyers (DDG). The deployment of multiple assets increases the level of complexity in creating mission plans needed to execute military operations.

The sheer amount of information needed to build a mission plan and utilize tactical assets can be difficult to fully understand and visualize via a 2D representation (i.e., PowerPoints, equipment manuals, flat maps). In the 1800s, Clausewitz noted that war is a combination of friction, chance, and uncertainty and is still relevant today which burdens the ability of commanders to constantly remain responsive, versatile, and adaptive and simultaneously create and seize all opportunities to reduce their personal vulnerabilities as best as possible [48].

With the understanding that planning a mission for multiple assets increases the level of complexity to accomplish a Commander's intent, studies have shown the benefits of AR technologies to achieving the same mission plan but in a faster and more effective way. By representing information in traditional 2D like PowerPoint, there is a limited manipulation of the content of the data, and one must download the PowerPoint document, update the information, save it, and resend the same PowerPoint document. By representing information in a 3D approach using AR, multiple users can simultaneously manipulate the same 3D virtual object, supporting mission planning, decision-making, and collaboration. With this more modern approach, 3D applications of information could have the potential of "clearing the fog" for commanders to build more comprehensive mission plans and improve situational awareness among multiple decision-makers.

3. Mission Planning Applications with AR

Collaboration between multiple users suggests the existence of a standard of knowledge when it comes to the operational picture. That is not always true due to hearsay and out-of-date reports and just the complexity of multiple entities working together. By introducing immersive technologies, the ability to have real-time 3D representation of an operational picture and the physical area of operation determined for collaboration can highly assist mission planners. Several studies have been conducted using AR technology that observed mission planning and collaboration among users both locally and remotely.

Kase et al. research titled "Observations of Individual and Team Understanding in Augmented Reality Mission Planning" addresses the challenges associated when application of AR in mission planning task [50]. The study asked subjects to use 2D and 3D visualization technologies to plan a mission to achieve a specific objective by manipulating the military symbology as if it were their soldiers to deploy in a specific way. Figure 12 exhibits the prototype of Kase et al. mission planning scenario using the HoloLens to represent the scene.

Figure 12. Enemy-held terrain model visualized with the HoloLens showing mission variables and an example of COA. Source: [50].

A surprising result of the pilot studies was how readily the participants collaborated while using the technology [50]. In the HoloLens condition, where each team member wore a device, the team naturally and rapidly devised a method for collaborating and establishing a common understanding. Sometimes they would take turns during the route planning, and other times the individuals would divide up the tasks required to develop the course of action (COA). Other results suggested potential benefits beyond the mission planning scenario, such as how AR supported quicker decisions and established a common understanding across team members faster [50].

Several other authors used AR for mission planning purposes. For example, Jenkins et al. delved into three Microsoft HoloLens prototype AR applications specifically to identify the strengths and weaknesses these applications for mission planning and decision-making [51]. The three prototype AR applications that were visualized were (1) the terrestrial battle space, (2) the common operational picture (COP), and (3) the space situational awareness to examine any constraints experienced by users within HoloLens [51]. The study examined multiple ranges of AR visualization to determine different perceptual issues within the prototype; they were also interested in the strengths and weaknesses of the setup. Figure 13 shows the issues with scaling effect.

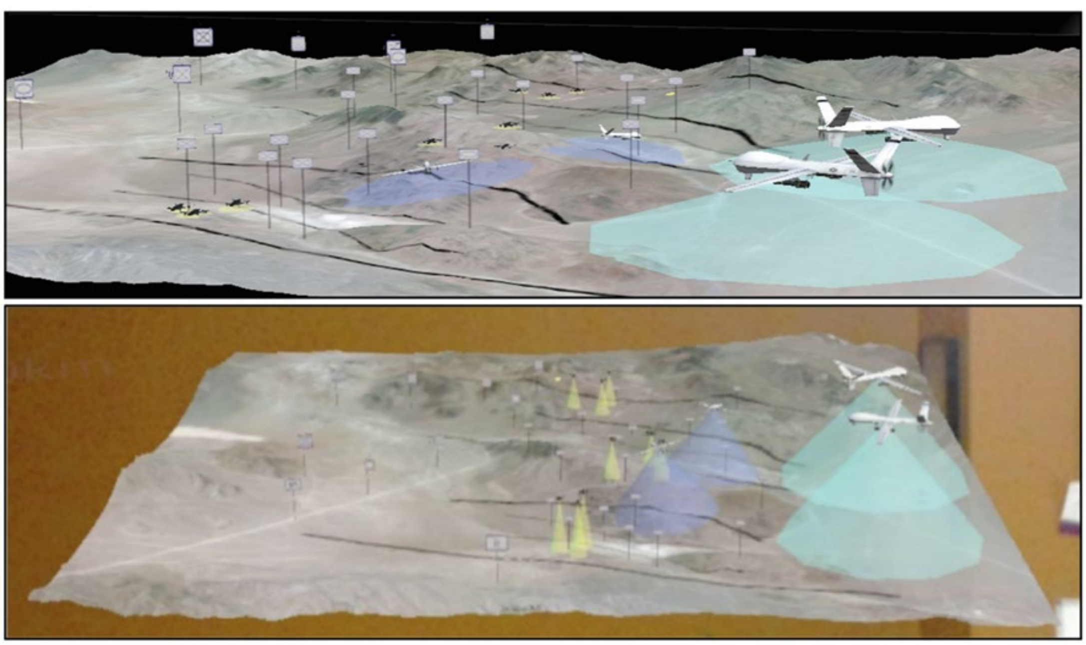

Figure 13. AR scene illustrating issues of scale based on the terrain scale. Source: [51].

Their findings noted "potential benefits over traditional 2D, screen-based geospatial displays seem to primarily result from the potential ability to better visualize spatiotemporal information related to: (1) dynamics of the battle space (e.g., shifting view scales, changing viewing perspective); and (2) visualization of volumetric intangible information" (i.e., ranges, and impact area) [51].

Overall, Jenkins et al. [51]. study focused on the different visualization challenges presented using AR, a new technology that most users are not familiar with. It was found that users tended to revert to what they were used to, and scaling in the visualization was vital in their comprehension of the overall scenario. Even though collaboration was outside of the scope of Jenkins et al. work, there were potential benefits of using AR technology when it came to its interactivity and its potential for collaboration. Nevertheless, it is known that the uniform translation and transformation of traditional 2D design strictly onto a 3D design using AR would not benefit users; the same issues may contribute to AR application abandonment [51].

AR systems have the potential to improve tactical SA and increase information superiority within combat forces through an individual's ability to use AR to consistently register and combine both real-time physical information from the surroundings virtual 3D information originally provided by multiple battlefield management systems and intelligence systems.

To maintain U.S. information superiority advantages, the U.S. military may consider the research conducted by Kenny R.J. who adamantly argued for the implementation and leveraging of AR technology [52]. His research focused on using AR systems at the tactical and operational levels to provide each service branch with the ability to improve different tasks. The author also states that the use of AR systems by operational leaders and their staff would provide expanded abilities in understanding complex operating environments and direct tactical forces. At the tactical level, AR can assist with the ability to observe, identify targets, deploy kinetic attacks, and identify the location of friendly forces. At the operational level, AR can assist with improving decision-making through the visualization of complex environments. Furthermore, AR provides leaders the ability to assess the effectiveness of their actions through multiple perspectives.

However, the multiple benefits of implementing AR systems coincidently bring challenges to the operational level and tactical level. Outside of connectivity issues that could limit the functionality of an AR system, social challenges could also be introduced when adjusting to new technology. In addition, data security and privacy concerns can arise when collecting classified data. The author believes that, unfortunately, the military's biggest challenge is the micromanagement of senior leaders due an abundance of information gathering technologies that provide more information but less standardization to interpret the vast amount of complex information [52]. Even though micromanagement will continue to be a problem that leaders will have to overcome, the benefit of AR resides in the ability to comprehend complex tasks to promote cohesion among leaders. Kenny concludes his research by urging the military to adopt AR systems to increase decision-making at the tactical and operational level as well as preserve information superiority advantages.

G. EXISTING DATA AND NETWORK VISUALIZATION

1. Data Visualization History and Definition

Data Visualization represent a variety of techniques employed to make information like diagrams, easier to understand; the same approaches but must also include enough pertinent and reliable information to support real-time operations. The same techniques emphasize interactive, visual representations of abstract data to strengthen absorption of information by human users [4]. Ideally, visual representation of the data should provide users with the ability to interpret and understand the information without any training or assistance from others.

Humans used data visualization techniques for many centuries. Data visualization that we associate with maps dates to pre-17th century when maps and diagrams were used to distribute information. The earliest evidence of visualization can be found "in geometric diagrams, in tables of the positions of stars and other celestial bodies, and in the making of maps to aid in navigation and exploration" [53]. In the 1700s new graphics were developed in attempts to show more than just information on paper.

As an example, maps made before 1700 would only show the geographical area of a map while maps made in the 1700's, like in figure, additionally incorporated lines to show equal magnetic declination. As time progressed, "abstract graphs, and graphs of functions became more widespread, along with the early beginnings of statistical theory (measurement error) and systematic collection of empirical data. As other economic and political data began to be collected, some novel visual forms were invented to actually portray them thus having data 'speak to the eyes'" [53].

It was not until the 1800s where the beginning of modern graphics came to fruition, which used graphical displays to understand complex data further visualizing different types of data. Furthermore, up through the 19th century, as widespread data collection and statistical thinking increased, there was a need for more data visualization for commerce [53].

Over time the advancement of technology expanded the ability to revamp quantitative information from 2D layouts of information to 3D layouts. Today, data visualization in AR allows users to have a virtual experience made from hundreds of data points originally inputted into a device to create the best 3D visualization of information. Because of this, user engagement with 3D data further advanced technology to project an understandable view of information while using immersive data visualization. Tying it back to study presented in [51], data visualization ultimately speeds up the development in performance, providing positive results when displaying information in the 3D vice with the traditional 2D information.

2. Managements of Computer Networks

Network management functions allow users to manage user accounts and network resources. Network management using AR then interconnects these systems and facilitates the availability of real-time data and asset information. That is essential to mission planning to assist decision-makers in understanding the current state of assets and their corresponding resources to plan out military tasks. Furthermore, network management provides sustainability between networks and the ability to predict behaviors and faults within a system and safeguard a network infrastructure. So by using AR systems, it can better provide an effective visualization of network infrastructure and topology for decision-makers to leverage during the planning process. In other words, creating an interface that is based on the images of physical real space to easily identify specific wireless devices will certainly help visualize wireless networks using AR technology [54].

Network Infrastructures can be extremely complex and require understanding every meticulously interconnected system, its nodes, and devices. Individual protocols are managed differently by different network devices, and each has its vulnerabilities along with optimal operational parameters. For example, each time a network device is added or removed from the architecture, the protocol diagram must be updated, and the network topology re-adjusted to make room for the physical state [4]. Because of this intricate integration, the complexities within a network infrastructure easily cause confusion among leaders and users of these interconnected systems. AR systems can provide the functionality to maintain the network database and an up-to-date infrastructure more readily than the traditional 2D blueprints of a single working diagram. Applying AR to network infrastructures can thus enhance situational awareness for resource management of devices connected to the network and the comprehension of the broader scope of assets.

3. Media Richness Theory

With the ability to visualize information and manipulate objects in 3D, studies have shown that AR promotes collaboration among users and enhances decision-making MRT contributes to our understanding of the data visualization and allow us to understand the way in which communication and collaboration can be successfully accomplished. Those ideas also demonstrate how human beings consume information individually and in the presence of others.

MRT identifies the four factors that influence media richness: the language variety, the immediate feedback, the medium’s ability to transmit multiple cues, and the personal focus of the medium [55]. Figure 14 shows the low and high richness of information. So, using a persistent AR makes information more understandable and thus quicker to analyze for collaboration.

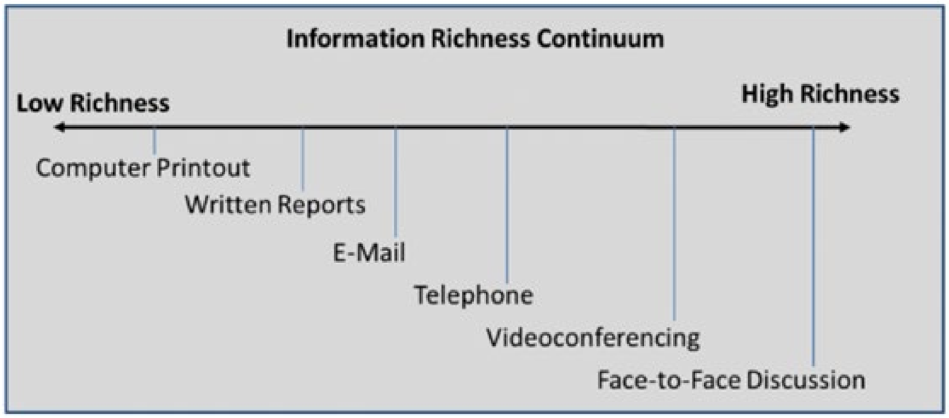

Figure 14. Information richness continuum. Source: [55].

"The richness of a medium mainly depends on the possibility for immediate feedback, number of simultaneously usable communication channels, the degree of personalization, and diversity of languages" [56].

4. Applications of Network Visualization

In the early years of VR systems, it was found that one immediate useful application of that technology was to visualize scientific data to better understand the complexity of data, stereoscopy, and interactive exploration [57]. Furhmann et al. [57]. study discusses how AR combined with data visualization presents an ideal working environment for collaboration. The authors used an existing Advanced Visualization System (AVS) to construct dataflow networks to provide better data visualization in support of collaboration. AVS used a graphical way to visualize these flows of data in networks within the AR system as their main objective ultimately allowing users to familiarize themselves with the system [57].

Synchronized data is essential to updated servers; therefore, any changes to the AVS were instantly updated and synchronized with the display server that provides real-time data and users' perception and relative position. Since user feedback is essential to the interaction of objects with visualization, the study focused on personal interface, custom views that allowed users to decrease the amount of data projected, reconfigure newer dataflow networks and the occlusion of images. The results showed that users liked the ability to see objects from different perspectives by walking around, above, below, and even stand in the middle of it [57]. Users noted that they wanted a global feature of the system and local features to shift their point of view (POV) of the data presented to them. Furthermore, users criticized that HMD had a small viewing angle, low resolution was notable but wasn't too significant, there were registration errors, there was some lag, and wished there was an accurate positioning method to better understand the specific numbers [57]. The research concluded virtual space enhanced collaboration and increased the acceptance of virtual objects.

Sato et al. proposed a platform that provided the availability for visualization and the management of wireless networks using AR technology. A visualization application was necessary for operators to manage complicated wireless networks. One of the objectives of network visualization is to introduce wireless devices and applications to network infrastructure, allowing users to manipulate images in real-time.

Currently, a visualization of information into a visualization application is created when information is taken from both wireless devices and their networks who are then mapped to their respective wireless device onto 2D space [54]. There were three common visualizations in a visualization application: visualization of the links, visualization of traffic, and visualization of wireless device information; however, only a few functions within the visualizations were implemented.

As wireless devices and their virtual counterparts increase over time, identifying and matching wireless devices in real space based on information in the virtual space, has increasingly become more and more complex [54]. The authors developed a framework to support multiple wireless communications while interconnected with applications to manage networks using visualization to interact with real and virtual objects. The results of performance evaluations also demonstrated that the platform did not introduce performance issues [54].

Karaarslan [58] study proposed a cyber situational awareness (CSA) model meant to give better SA on cyber security threats for network administrators and their respective systems. That research examined an established situational awareness model and surveyed cyber security practices and tools to extend that knowledge to actual CSA [58]. He also focused on the configurational, operational, and special conditions awareness of CSA as seen in Figure 15.

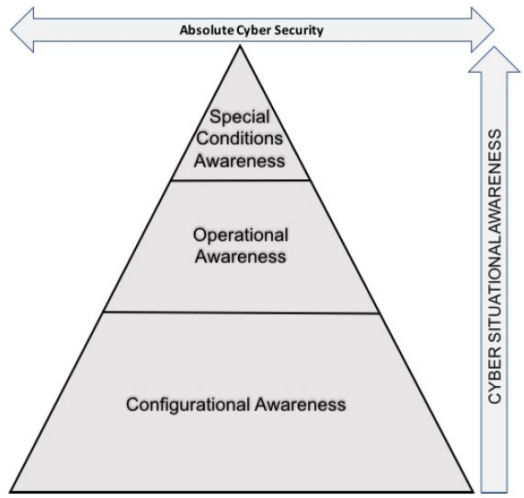

Figure 15. CSA pyramid. Source: [58].

Administrator's CSA increases as you travel upward on the pyramid ultimately representing the reduction of logical complexity of a cyber system [58]. Configuration awareness is the configuration of a network database, operational awareness is the identification of threats and vulnerabilities, and special condition awareness focuses on user interaction with a system. To ensure leaders maintain awareness, it is the responsibility of decision-makers to have clear objectives for complex systems instead of trying to manage tasks one by one. Additionally, there is a velocity of data in these complex networks that leaders must be cognizant of since it adds more complexity to the system and makes it is harder to maintain, but the CSA pyramid was proposed in order to decrease this complexity and help maintain awareness of the critical cyber security data.[58]. Implementing a model for a clearer understanding of the cyber domain while training users will enhance situational awareness to support accomplishing objectives.

H. CHAPTER SUMMARY

This chapter examined the literature sources that provide key concepts and topics in support of this research. It reviewed AR technology, visual displayed used for AR solutions, cybersickness and its symptoms, MRT, persistent systems and collaboration, Pervasive AR, mission planning and AR applications in support of mission planning task, network management and network visualization.

III. TASK ANALYSIS

A. INTRODUCTION

To create and implement a 3D application to assist decision-makers and warfighters with the ability to visualize and understand communications onboard surface vessels, the characteristics of tasks must first be understood as it is currently executed in the Navy. Today, the Navy uses multiple tools to understand and disseminate information through the naval battlespace; however, there are limitations and misinformation that is delivered based on a surface vessel's operational state. The operational state can have the following characterizations: ship-specific systems that are either fully operational, degraded, or non-operational. These communication tools include PowerPoint documents, verbal exchanges of information, chat messages, message traffic, and voice circuits both on the classified and unclassified level.

The current tasks must be analyzed to evaluate the need for 3D applications to enhance understanding of these complex information systems. Thus, an implementation of the PAE must meet the current objectives of current tasks and allow users to achieve the same requirements by refining current practices. As defined by usability.gov, task analysis is the process of learning how ordinary users perform their tasks and achieve their intended goals [59]. Among other things, task analysis includes how users perform tasks, the steps required to accomplish tasks, the number of users needed to accomplish the tasks, the present conditions during the execution of tasks, and the set standards to accomplish the tasks. This chapter will analyze the current practices, decision-making, resource management of equipment, and service availability across the Fleet, specifically for information operations within the cyber battlespace.

B. DEFINITIONS

1. Chain of Command

In Joint Publication 3 Chapter 2, Section "D.ii. Levels of Mission Planning," [47] the three levels of war were previously defined as strategic, operational, and tactical level. Those levels demonstrate the tiers of SMEs that are necessary to conduct successful mission plans. In this thesis, we will focus on the tactical level of mission planning consisting of a single CSG made up of a single Carrier (CVN), a single CG, and three DDG. Furthermore, the tactical level was chosen for the scope of this thesis as CSGs are the naval physical assets that will go into battles and engagements to achieve military objectives. Since information operations do not occur physically in three dimensions, but in the fourth dimension, understanding the cyber battlespace, or environment, is increasing in importance when planning engagements to achieve specific military objectives.

2. Environment

Over time, the terms battlefield and battlespace have been used interchangeably to describe parts of an environment where "battles, engagements, and other tactical actions are planned or conducted" [60]. Furthermore, the concept of the battlespace is now based on one's forces' capabilities and actions in combat in that specific space where "the term battlespace itself implies a tactical, not operational, or strategic, level of war" [60]. Since cyberspace is a legitimate emerging and growing environment in which battles and engagements can now occur, it is a "new dimension of warfare must be fully understood" [47].

Through these definitions, the cyber battlespace can be defined as the space where surface vessels communicate, regardless of the physical distance of hundreds of nautical miles on the open ocean, by accessing satellites to retrieve communication services or using a line of sight. This consistent and persistent connectivity to communicate enforces a faster understanding of a mission that is being tasked and constant updates to situational awareness, further increasing the probability of making informed decisions regarding who, what, when, where, and how military objectives can be met.

> Cyberspace is a global domain within the information environment. It consists of the interdependent network of information technology infrastructures and resident data, including the internet, telecommunications networks, computer systems, and embedded processors and controllers. Most aspects of joint operations rely in part on cyberspace, which reaches across geographic and geopolitical boundaries—much of it residing outside of U.S. control—and is integrated with the operation of critical infrastructures, as well as the conduct of commerce, governance, and national security. [47]

Based on the above quote, the importance of understanding the cyber battlespace to effectively conduct mission planning is vital and current practices must be analyzed to leverage innovative technologies and quickly improve the level of understanding specific to the cyber domain. Cyber is a unique warfare area because systems are interconnected together to provide necessary requirements to meet a commander's intent. "Commanders must consider their critical dependencies on information and cyberspace, as well as factors such as degradations to confidentiality, availability, and integrity of information and information systems, when they plan and organize for operations" [47].

By leveraging the knowledge and information accessed from the cyber environment and leveraging the capabilities of AR to present information through 3D visualization, it will result in better comprehension and faster decision, improving mission planning and situational awareness.

C. TRADITIONAL PRACTICES AND REPORTING

1. Background

Currently, decision-makers rely on receiving information through multiple communication outlets that maintain the COP of a specific Fleet. Additionally, they depend on constant updates on their respective surface vessel's operational states to evaluate if mission requirements are being met. This information is presented through traditional reporting via four types of reports or communication outlets: voice, PowerPoint documents, message traffic, and chat. Each type of report is a redundant form to ensure information is disseminated throughout a CoC. Once consolidated, the information builds the COP to visualize the overall battlespace of the Fleet. Information is then passed throughout the CoC to be transmitted in a time-sensitive manner.

Furthermore, this large amount of information must be clear and concise for both subject and non-subject matter experts to easily comprehend the operational state of multiple assets in the Fleet. The Navy uses these traditional ways to communicate and track a ship's overall operational assessment regarding multiple warfare areas (i.e., cyber network, weapons status, combat system abilities). For mission planning, high-level decision-makers at the strategic level (i.e., Fleet Commanders, Carrier Strike Group

Commanders) must rely on this conglomeration of data to understand the vast scope of an entire Fleet's equipment status and availability of services. That results in a plethora of chat or voice reports that turn into hundreds of PowerPoint slides that are pushed up the operational CoC to capture the current Fleet battlespace and maintain situational awareness.

Unfortunately, the nature of this cycle is that it inevitably includes a latency in information transmission if we consider the time when an update occurs and the time when the specific decision-maker receives it. Furthermore, the use of different communication platforms when reporting to higher levels causes information to become error-prone; this happens due to the constant equipment and service availability changes resulting in warfighters misunderstanding information. The findings of the study done by Jagears [61] support the desire to move away from PowerPoint briefs to a more effective representation of statuses and service availability.

2. Task Description

The Commanding Officer (CO) on a surface vessel is responsible for the operational state of his or her ship and executes given tasks, or orders, by his or her superiors. The CO, however, makes decisions solely based on the information briefed by his or her staff. The brief includes inputs from several Officers onboard who act as the SMEs in their respective fields; however, for the scope of this thesis, we will be focusing entirely on cyber and thus the Combat Systems Officer (CSO) or the Operations Officer (OPS). Both CSO and OPS brief the CO on the current communication statuses and how it will impact operational events the ship is tasked to complete.

Specifically, surface ships rely heavily on communications, including networks, to communicate with other ships for any operational event. Thus, any communication casualties must be reported verbally and restored within a specific time frame to ensure communication is maintained and meets the operational requirements. The Communications Officer (COMMO) is the person in charge of maintaining the communications and information systems onboard the ship, providing the CO with cyber situational awareness. Depending on the time it takes to restore equipment, a communication spot (COMMSPOT) or casualty report (CASREP) must be drafted, approved by the CoC, and sent from the ship via message traffic to inform multiple commands of the casualty and determine if assistance is required.

Because of the inherent characteristics of the traditional communication systems, a considerable time is dedicated to communicating within a ship, between multiple ships, and communicating to a higher level. For example, a Fleet Commander could require daily cyber statuses of the ships in his or her AOR. There are three CSG within an AOR, each with a BWC. Each CSG could have five to six ships that must report their daily cyber status up to their respective BWC. If each ship reports its cyber status to their BWC at 1200 Greenwich Mean Time (GMT), then the BWC reports to their CSG CO by 1300 GMT, and then the CSG CO reports to the Fleet CO by 1400 GMT. However, by the nature of the initial reporting time, that information is far too late and not current.

The initial reporting time for a cyber status does not include the time required of the COMMO on the ship to draft the message, verify with the SMEs that it is correct, produce a recommended solution, and brief the CoC to receive approval or disapproval of the message. Once the CO grants approval for the message to be released, the message must be uploaded to a message system, thus adding more time to inform the CO's immediate superiors. Ultimately, the amount of time it takes to report casualties exceeds the timely submissions of COMSPOT when an outage lasts for thirty minutes.

3. User Characteristics

The decision-making process for communications involves multiple personnel onboard a surface vessel but involves two departments: Combat Systems and Operations Departments. Both the COMMO and the Information Systems Officer are "responsible for the organization, supervision, and coordination of the activity's communications, in addition to management of connected internal radio systems and ensuring the networks operate in an efficient manner" [62]. The COMMO is usually designated as an Information Professional (IP) Officer who specializes in communications; however, some Surface Warfare Officers (SWO) may hold that position.

Ultimately, the CO is responsible for the communication suite; therefore, the CO relies on the COMMO to understand any impacts of communications on and off the ship. The CO is regularly briefed on communications and relies on the SMEs to carry out the commander's intentions to meet the mission. Furthermore, SMEs constantly collaborate to assess the operational state of the ship and keep the CO informed to limit any impacts or casualties. To ensure communications are always operational, it is the responsibility of all personnel who utilize information systems and voice circuits to constantly monitor the equipment that is used and report any abnormalities to be investigated by the COMMO.

4. Tools

In the current task, communication on and off the ship is accomplished by chat and voice circuits. The SMEs are expected to brief the status of equipment daily to the CO so that the CO can assess the operational state of the ship, make plans to correct it, and send it up to his or her superiors. By doing so, the higher-level decision-makers can have an informational representation, or situational awareness\ of the operational picture through these briefs. In other words, these daily briefs maintain situational awareness if the commander's intent has to be modified for an operation or mission.

Specific to the SMEs onboard a surface vessel, the Combat Systems and Operations Departments, and Combat Information Center consolidate a multitude of official messages i.e., Daily Intentions Messages (DIM), Weekly Intentions Messages (WIM), Operational Order (OPORD), Tasking Order (TASKORD), on a daily basis in order to understand a warfare commander's intent and also maintain the required communications onboard a ship. In addition, the COMMO must use multiple messages to build a communications plan to establish communications with off-ship entities.

Operationally, the availability of the communication tools onboard a surface asset depends on the state of the communication equipment. That includes SMEs locating the footprint of satellites, the ship's geographical position, the environmental conditions, and the actual equipment that can impact the service availability of a communication suite in preparation to rectify any communication casualties. As noted, multiple conditions can impact services; thus, the delivery of verbal and non-verbal reporting can be delayed, and the actual operational status of a surface asset might not be accurate.

5. Success Criteria

The traditional amount of work and time to draft a single Navy message is significant for a single command. When applying the same message drafting time throughout the entire Navy, a single message is multiplied by hundreds of messages based on reporting requirements, and unfortunately, daily messages must be sent out in a single day which exponentially increases the work and time for commands. For example, the reporting standard for Operational Report-3 (OPREP-3) messages states a voice report must be conducted within 5 minutes of the known casualty, and a record message report must be within 60 minutes. Even though both reports have the same content for redundancy purposes, there are clear differences between the two. Since OPREP-3 messages require immediate attention due to the severity of the situation, the voice report must be transmitted faster with fewer details. The message report, however, has more time for reporting to ensure more details are gathered for leaders to understand the situation at hand. Since there is an emphasis on the immediacy of the report rather than content, the initial report will not have all the detailed information. That allows higher-level leaders to understand that there is a casualty or problem, and start readdressing the situation, also known as mission planning. The delay of reporting due to lack of information is discouraged since real-time information of a downed system is more important to allocate different resources and immediately remedy the situation as soon as possible.

Specifically, drafting a message report can be generalized for any type of Navy message, PowerPoint document, or verbal brief. First, a message is drafted with the initial information and required format. That could take from 5 minutes to 30 minutes. Next, the message is routed up to the first level of CoC for Chop (also known as "verification" from your superior that the message is correct to continue the process). That could take from 5 minutes to 30 minutes to make corrections and then re-chop until the first level of CoC authorizes the correctness of the message. After this, the message is authorized or signed, and then taken to Radio Central (the physical entity onboard a ship authorized to send out

Navy messages) to be logged in Date Time Group (DTG) order in a central message log. Lastly, the message format is verified by Radio Central to verify format, administrative addresses (DTG, routing indicator, and pro-signs), inputted into a messaging system to be distributed internally (Electronic Message Traffic) and externally off-ship via Message Traffic. That process could take up to 20 minutes, based on the message's order of precedence and the overall message queue from the day. A unit always receives a comeback copy of a message to verify the message was successfully transmitted internally and externally.

As demonstrated, the number of personnel who chop the message for the CO to approve a single message takes a significant amount of time to generate an accurate message off the ship. Sailors have to verify the status of the system and decide the appropriate steps to accurately troubleshoot a single piece of equipment, which significantly increases the time to generate an accurate message. Additionally, different commands have different internal reporting requirements specific to their command. That can include reports from daily status updates (Daily 8s) to show the equipment status of the communication capabilities of a single surface asset, which can be in the format of a PowerPoint document or a verbal brief. Those actions further increase the time between drafting the report and requesting approval to submit it to the authorizing decision-makers before it gets to the CO. More time is added when briefing the CO on any updated information on equipment or systems, and finally, time is added when one includes the CO's comprehension of the status change and making a decision about the information. Again, the compounding of the number of reports and the time it takes to create those reports exponentially increases the amount of time to affect a decision in mission planning.

D. CONCLUSION

The current tasks outlined in this chapter are complex and require high levels of understanding and constant information flow to support mission planning. By examining these tasks and associated users involved in network operations, we have determined success criteria for implementing the visualization of 3D information. The success criteria are the baseline for the PAE system's technical framework to enable effective and efficient comprehension of the cyber domain and optimize decision-making.

1. Traditional vs AR Time

A recommended solution for the time-late data would be to utilize a PAE accessible to everyone and updated on a real-time basis and visualize complex systems to support more efficient decision-making. That includes visualization and understanding of the data originally presented by the PowerPoint briefs (in this case, the cyber battlespace). By having this type of 3D visualization application with continuously updated data sets, PAE provides more flexibility to display complex systems like the cyber domain, enhances knowledge of the interconnectivity of cyber networks, contributes to effective interaction with real-time data, and improves comprehension of decision-makers. Visualization of the cyber domain could potentially meet the traditional success criteria and minimize the time leaders need to identify and report casualties, providing a better understanding of the operational picture.

Additionally, the purpose of the PAE system is not to eliminate traditional messages via message traffic, but to become a high quality, effective tool capable of assisting the higher-level leaders in their assessment of surface vessel operational state and quickly identify casualties that could impact a mission in real-time for an entire Fleet.

E. CHAPTER SUMMARY

This chapter elaborates on tasks that constitute mission planning relevant to the cybersecurity domain and highlights the issues that current practices pose to the personnel responsible for those tasks.

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IV. SYSTEM PROTOTYPE

A. INTRODUCTION

This chapter describes the framework used to design and develop the PAE system architecture, a set of 3D models that represent virtual environment, virtual (simulated) environment, and PAE interface. The goal of this prototype is to visualize complex communications and networks onboard multiple ships and identify if this visualization allows the users to identify the status of its networking resources. For example, they would be able to identify communication casualties that occur over time. The system prototype is designed to enhance single user comprehension and situational awareness, thus making DON mission planning efforts more effective. At the tactical level, this research will assist in developing further understanding of technological infrastructure and processes onboard surface vessels that need to be established to support effective mission planning. The overarching concepts and functionalities of the PAE system have a potential to bring notable benefits to all DOD services. A four minute and fourteen second “Short Video Demonstration of PAE Overview_1 of 3,” an eight minute and four second “Long Video Demonstration of PAE Functionality_2 of 3,” and a “PowerPoint Brief Thesis Overview_3 of 3” can be found in the supplemental section of this thesis for a full visualization of the PAE prototype.

B. FRAMEWORK

1. Why Augmented Reality?

As discussed in Chapter II, AR allows participants to visualize virtual information displayed around their physical space and support seamless communication and interaction with 3D objects. HoloLens 2 device provides participants with the ability to present information in 3D form and allow for intuitive interaction with the data sets. The use of AR visualization technology and 3D data that replace sets of 2D information has a potential to decrease the amount of time it takes to determine the status of equipment from a single surface vessel all the way up to the Commander of a CSG. That, in turn, will increase the time to comprehend the information and form an optimal solution. One may say that there can be a danger for higher level leaders to “interfere in operational or tactical decisions that should be handled at a lower level” [63]. However, there is also a possibility that AR systems could help “increase situational awareness and empathy with the organization it commands. In other words, give tactical leaders the capability to be “eyes on/hands off” [63]. By having an “eyes on/hands off” ability, AR systems can be an additional tool used for quicker response and shorter decision time. Additionally, the real time data is non-existent when reporting casualties because the information is time-late due to the reporting chain. Therefore, using AR will equate to instantaneous SA on the COP.

Furthermore, a see-through AR visual display is more suitable in the Navy and onboard surface vessels for safety reasons since surface vessels are affected by sea state. Because of that, one must have the ability to safely maneuver onboard a ship that is already mobile and still see superimposed 3D objects by the means of a see-through AR display. In other words, ships are constantly moving depending on the severity of the sea state or speed of the vessel; therefore, AR is the best option to present 3D information to maintain safety. Furthermore, unlike VR display that blocks off all visual elements of the immediate (physical) environment, an optical see-through AR display has a transparent visor where users can constantly be aware of their physical surroundings without any obstructions and simultaneously engage in conversations and collaborate with other people as needed.

Utilizing a desktop computer display and corresponding interface could be a solution to view the information. However, based on the already limited number of computer assets onboard, that would take away from other shipmates needing a desktop to conduct normal daily operations. While wearing an AR display, a user can move freely around the ship and not be restricted to one location. Additionally, if there is a need for collaboration, desktop computers do not allow face-to-face engagement, which could be detrimental for the team collaboration. Tablets may also be used to visualize information and present it to the users; however, they have a much smaller screen size and corresponding field of view. Like the use of desktop computers and their screens, the user typically focuses on the screen and loses capability to interact with other users in a face-to-face fashion. In conclusion, incorporating an optical see-through AR display to present information allows users to be co-located in a virtual environment, see each other at all times, and decipher information faster to support more effective decision making and situational awareness.

2. Why Microsoft HoloLens 2 (vs. Google Glass/Meta 2/Magic Leap)?

HoloLens 2 was selected as a device to project 3D information in an AR environment due to the capabilities of the software and compatibility with other AR applications. Since the 3D information requires attentiveness of eye and hand engagement, HoloLens 2 has great functionality to support the required gesture recognition. Regarding switching from seeing AR to seeing only the real world, the user has the flexibility to leave the headset on and look through the transparent lens (seeing real world and superimposed 3D objects) or to flip up the visor to see the real world in an unobstructed way. Whether the visor is up or down, the HoloLens 2 eliminates the need to remove the headset.

HoloLens 2 also has multiple mixed reality features developed to support object manipulation that was vital to our PAE system. The HoloLens 2 also has upgraded eye and hand movement tracking compared to its predecessor, HoloLens 1. That capability, combined with the Mixed Reality Toolkit (MRTK), allows for accurate interactions by participants who need to manipulate virtual objects.

Another feature that could be used in the future is HoloLens 2's ability to use remote assistance for data sharing and collaboration. That is an essential capability for the Navy since tactical leaders are not always physically located in the same location or even geographical area.

Compared to other leading AR headsets, HoloLens 2 was selected as the best suitable device to meet the tasks criteria detailed in Chapter III. Other headsets, like Google Glass, are not truly AR display solutions – they were designed to be used as monocular displays in combination with the smartphones. They also lack the tracking and gesture controls required for the type of manipulation of digital information. Meta 2 had more rendering power and a bigger field of view; however, it lacked the full wireless functionality we would need for mobility onboard a surface vessel. Lastly, Magic Leap had updated hand tracking capabilities, but was unfortunately known for losing some content in the peripheral vision.

Overall, HoloLens 2 support from Microsoft and its compatible applications meet the requirements of the PAE prototype and the objectives set for our research effort.

3. Software Development Environment

a. Unity

Unity is a cross-platform game engine and development platform that supports the creation of real-time visual experiences for simulations and games. Unity was selected as a development platform because of the multiple toolkits and assets that provide the necessary functionality and representation required for the PAE user interface. Based on the supporting documentation for HoloLens 2 and compatible free assets offered by Unity, any issues presented with the graphic user interface (GUI) and development were easily resolved.

b. Blender

Blender is a free, open-source modeling tool that assists users in modeling 3D objects. This application was used to convert 3D ship models into filmbox (.fbx) files and then exported into Unity to create the simulated environment. Also, we used Blender to create 3D objects that represented digital networks and communication topologies; those objects represented three different types of communication lines (voice circuits and chat) on the 3D model of the ships. These topologies were then similarly integrated into the simulated environment that was used in the usability study.

c. Microsoft Visual Studio

Microsoft Visual Studio (VS) is the integrated development environment (IDE) that was used to develop and write scripts for the prototype. VS allowed us to create a JavaScript Object Notation (JSON) file to store ship data, build and debug the code to output the information exported from the JSON file onto the heads-up display menus as 3D textual information.

4. Hardware Environment

The following hardware environment was used for the development of the PAE system:

- Microsoft HoloLens 2 device
- Alienware 17, 8th Generation Intel® Core™ i7-8750H, 32GB RAM, GTX 1080Ti Laptop

C. SIMULATION ENVIRONMENT

1. System Architecture and Initial Design Decisions

The prototype system architecture as visualized in Figure 16 shows the components required to create the prototype as a 3D interactive AR environment. The laptop used the Unity software to produce the models in a 3D environment as stated in the above section. Specifically, to project a virtual scene inside the HoloLens 2, the Mixed Reality Tool Kit (MRTK) and its corresponding Holographically Remoting feature were used. Furthermore, a Microsoft account was created to use the Microsoft Holographic Remoting Player App which was initially downloaded onto the HoloLens 2 headset. The internet protocol (IP) address from the headset was then connected with Unity's MRTK Holographically Remoting feature to finally connect and project the 3D environment from the laptop to the HoloLens 2, shown in Figure 16.

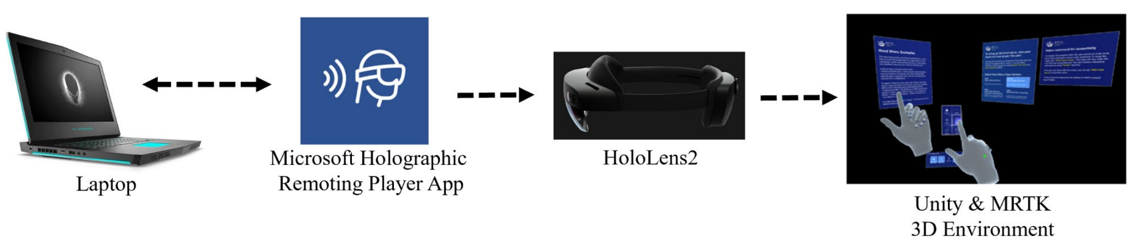


Figure 16. Simulation of development components.

2. Simulation Development

a. Microsoft Holographic Remoting Application

The Holographic Remoting Player application is a companion application that connects both PC applications and their respective PC games. By doing so, real-time streaming of holographic content using Wi-Fi connection is supported via Holographic Remoting through the PC to the Microsoft HoloLens [64]. The holographic remoting feature is a part of the MRTK that allows Unity to connect via an IP address with the HoloLens Holographic Remoting Player application.

b. MRTK Mixed Reality Tool Kit

MRTK is a collection of packages that enable cross platform Mixed Reality application development, and it provides a support for Mixed Reality hardware and platforms [65].

(1) Audio/Speech Controls

The HoloLens 2 has audio and speech capabilities with a microphone array of 5 channels and speakers with built-in spatial sound. However, for the purposes of this thesis, it was determined that the simplicity of hand and eye tracking movements would be the most realistic and easy way of assessing the functionality of this device. Additionally, the Naval ship has a constant noise due to sea movement on the ship's hull, the machinery running 24 hours a day, and a constant personnel communication with on and off ship entities, so the HoloLens 2 supported audio commands were not used.

(2) Actions/Gestures

Hand gestures are analyzed based on head tracking, eye tracking, six degrees of freedom (DoF) tracking, spatial mapping, and mixed reality capture to identify hand movements related to specific actions and gestures. Action examples include touch, hand ray cast, gaze, and air tap. Gesture examples (Figure 17) include selecting a button, hologram, selecting a hologram, moving a hologram, rotating a hologram, and changing the size of a hologram.

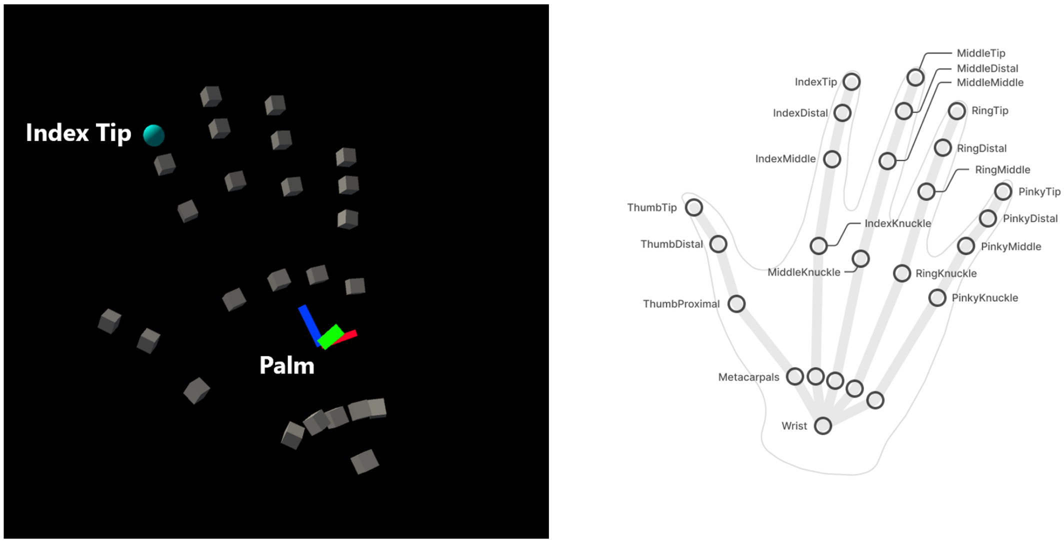


Figure 17. Visual of hand tracking sensor. Source: [66].

(3) 3D Environment

To create the 3D environment with a CSG, the CSG objects were imported from the NPS Scenario Authoring and Visualization for Advanced Graphical Environments (Savage) lab repository into Blender to combine all ship components into one object. This object was then imported into Unity. Once all ship objects were properly imported, we resized and positioned them in 3D world taking into account the limits of display FOV. After this, the specific communication network topologies were similarly imported into Unity. We used the objects that represented computer network in the system prototype developed by Matthew Timmerman [4] and manipulated them in Blender to display multiple networks. Lastly, we developed the scripts so that the ships could become transparent once they are selected (clicked on); having a transparent shell allowed the users to see the networks inside the ship.

(4) 3D Ship Models

We used the 3D models of CVN (Carrier), CG (Guided Missile Cruiser), and DDG (Arleigh Burke-class destroyer) ships from the Savage Lab repository at NPS.

(5) Integrated Communications and Network

The three distinct types of network topologies represented in three DDGs and CG were originally from a past student thesis [4]; we manipulated that 3D model to represent different types of communication networks needed for our thesis. The 3D model of each class of the ship (CG, DDG) shows the ship's shell with the three types of communication networks inside. The 3D models used in this study are approximate representations of current Naval vessels, and they do not represent an accurate model of the ships. Even though the models do not match current specifications, participants were provided with realistic representations that fully supported the objectives of our user study.

(6) Heads-up Display (HUD) Information Panels

- Ship Menus

Each ship has its own HUD information panel (otherwise known as communications menu) that displays the state of the three types of communication networks seen inside the skin of the ship. We imported JSON data to display specific information on the menu for each ship to indicate the state of the communication network based on a specified time. Additionally, a slider object was imported into the menu allowing the users to move the slider along the timeline to see the network status changes while simultaneously visualizing the same changes inside the transparent ship. The design of user interface enabled seeing the HUD information panel with the status about a single (individual) ship in Task 1 can be seen in Figure 20. In Task 2 and Task 3, however, the participant needed to interact with the menu that combines information about three DDGs, i.e., to see a multi-ship HUD information panel when selecting the CG ship label (Figures 18 and 19).

Figure 18. Individual ship menu.

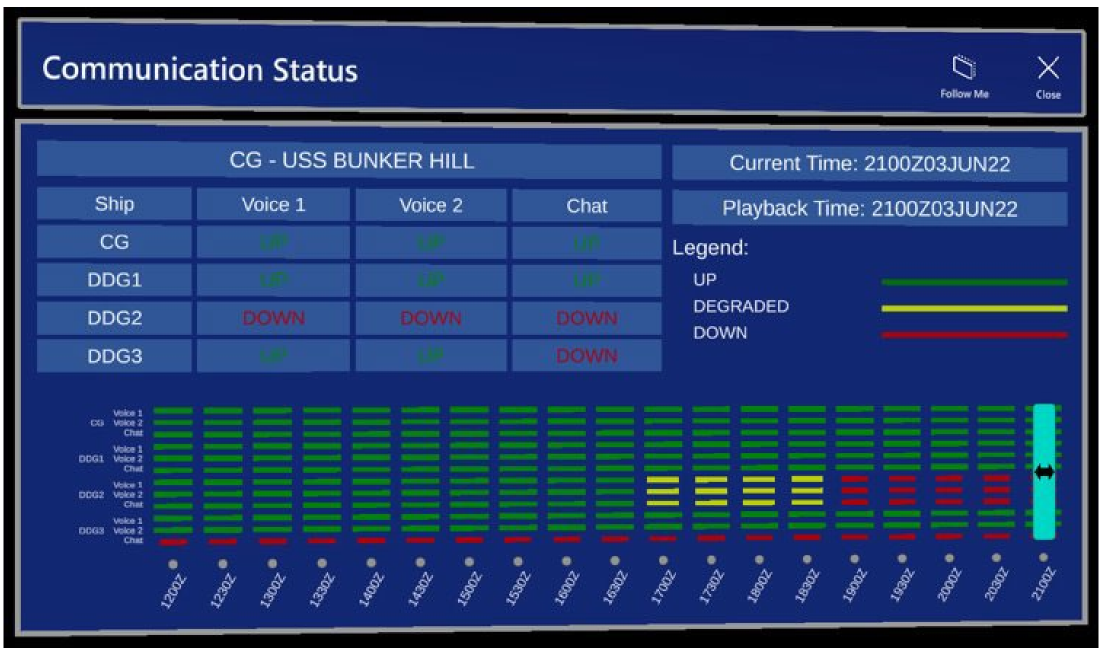


Figure 19. Multi-ship menu.

- Ship Labels

Each ship had a label attached to itself to help users easily identify the ship in the PAE. Once the user selects the ship's label, three operations were performed:

1. Change of ship's shell transparency. When the ship's label is not selected, the shell of the ship is projected as a solid surface (Figure 22), and when a user selects (taps) the label for the first time, the ship's shell becomes semi-transparent (Figure 20). If the user selects (taps) the ship's label for the second time, the ship's HUD information panel disappears, and the ship's shell re-materializes to the original solid color (Figure 21).

Figure 20. Ship label without selection.

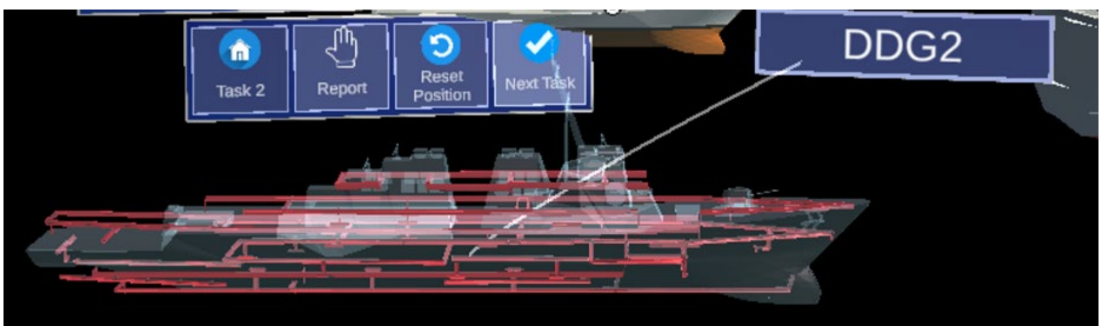


Figure 21. Ship label with selection.

2. Display of the ship menu. When the user selects the ship label, the respective ship's HUD information panel is displayed. That allows the user to easily visualize the status of the communication types as seen in Figure 22.

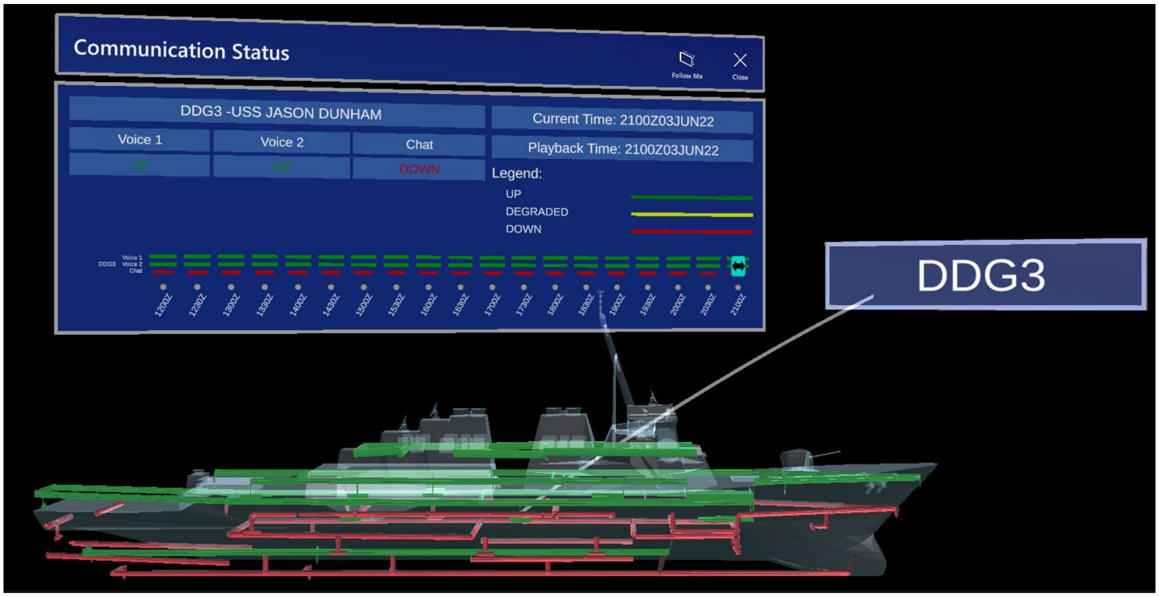


Figure 22. Ship menu displayed after the label is tapped by user.

3. Display of three communication networks. When the user selects the ship label for the firsts time, the three communication networks inside the ship are displayed in colors that correspond to the status of each communication network. If the user selects (taps) the ship's label for the second time, the communication networks disappear inside the solid shell (Figure 22).

D. TASK USER INTERFACE

When a user is initially introduced to the PAE application, a welcome menu is displayed with an invitation to select *Task 1* button and begin the study (Figure 23).

After the use begins the study, the scene changes to Task 1 Instructions (Figure 24) that provides a guidance for the first task. Selecting Start button starts the Task 1 and the panel with task instructions disappears. The user can, however, request the task information panel to appear again by pressing Task 1 button anchored in the lower left corner of user's visible FOV (Figure 25).

Figure 23. Welcome menu.

Figure 24. Task 1 instructions.

The anchored part of the task menu shown in Figure 25 consists of four buttons that allow a user to conduct four different actions. This menu always appears in the lower-left corner of the user's display, and it is accessible to the user at all times. The four actions made available in that menu are as follows:

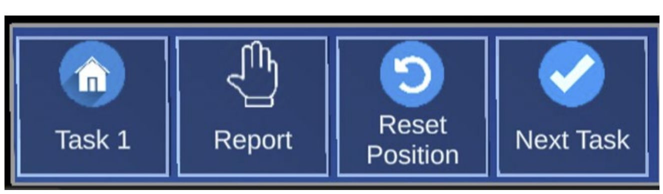


Figure 25. 4-button task menu.

1. **Task 1, Task 2, Task 3)**: This button allows a user to request a display of the instructions for that specific task. That panel (menu) will have a Continue button that will signal to the system that panel(menu) is no longer needed and that it can be removed (Figure 26 shows this example for Task 3).

2. **Report**: This button is selected by a user to indicate readiness to report the answer to the current task's question.

3. **Reset**: This button resets all the ship positions to their original positions. Since users can freely manipulate each 3D object, i.e., translate, rotate, and scale it, it was important to add a reset button so participants can easily restore the scene to its original state.

4. **Next Task**: This button directs the user to the next task.

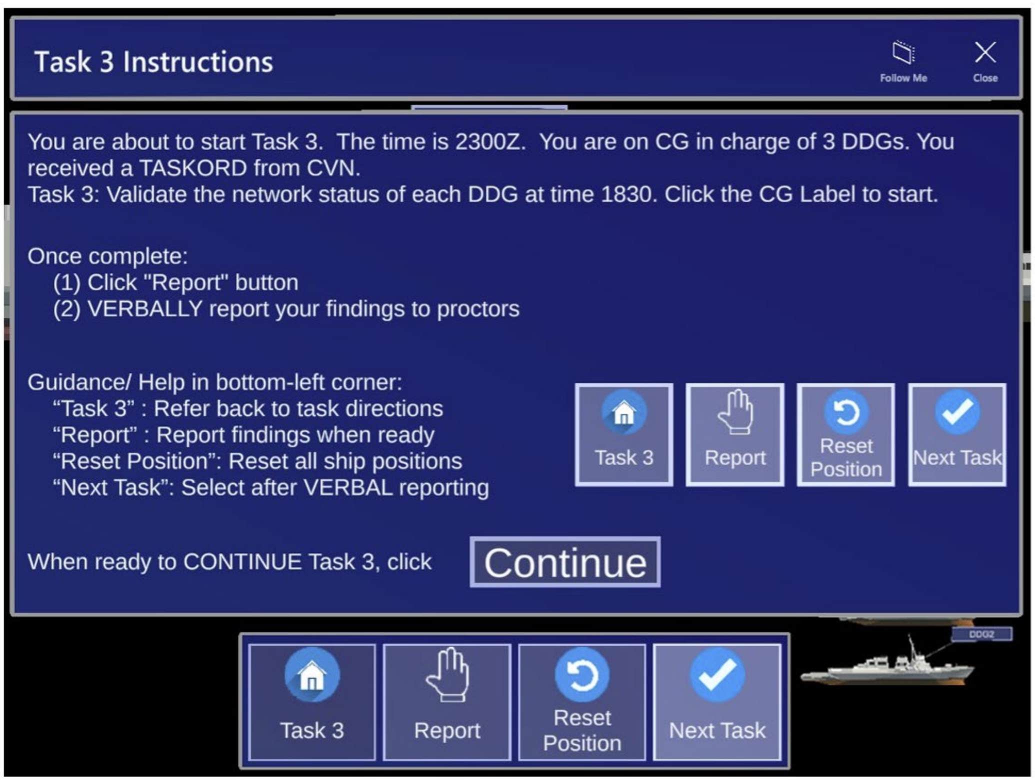


Figure 26. Task instructions menu with 4-button task menu.

a. Task Functionality

(1) Task 1 Scene

In Task 1, the participant sees a CSG on the sea that is composed of one CVN, one CG, and three DDGs, each with a corresponding ship label. At this time, only DDG2's label is active allowing a user to complete Task 1 as described later in Chapter V.

Selection of DDG2's label causes following actions:

- The shell of DDG2 changes from opaque to transparent.
- The user is presented with the DDG2 ship Communication Status panel (menu) that displays the timeline with information about three specific communication networks and their statuses within DDG2.
- The object representing communication networks inside DDG2 becomes visible within the hull of the transparent ship (Figure 22).

The limited ability to select only DDG2's label was incorporated to eliminate the possibility of selecting other ship's labels that are not a part of Task 1. The goal of Task 1 is to focus on a single ship, visualize its Communication Status panel (menu) and the corresponding communication networks.

(2) Task 2 Scene

In Task 2, the participant is presented with the Task 2 instructions panel and invited to start the task (Figure 27).

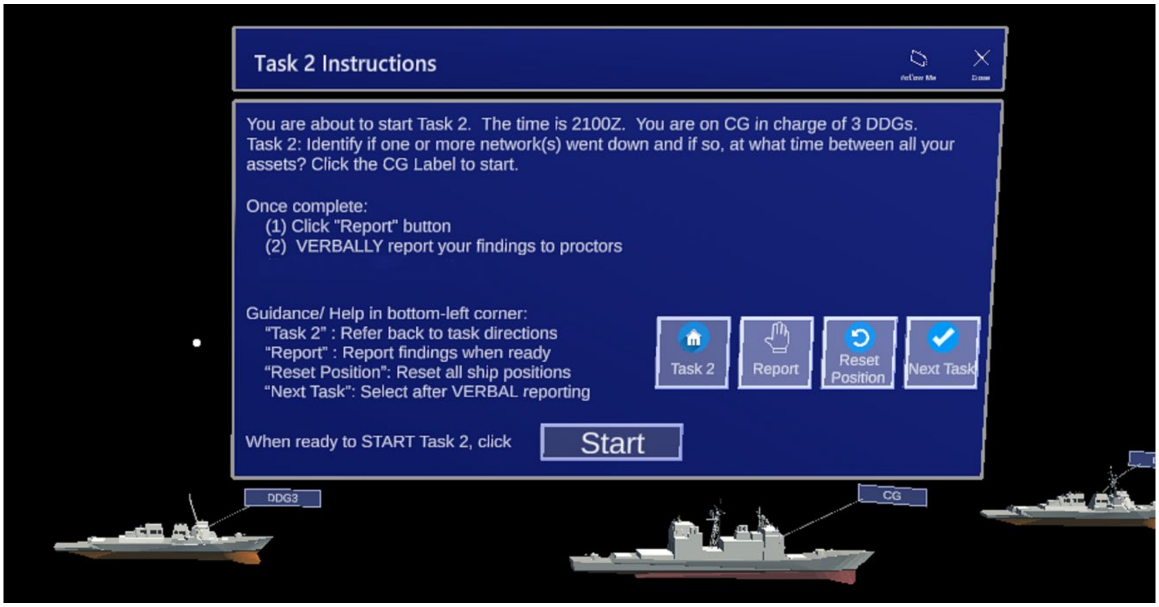


Figure 27. Task 2 instructions menu.

The objective is to visualize the information associate with multiple ships and report any casualties (communication networks being in degraded or down status) based on the instructions. The CG ship has command of three DDG ships and ability to view the CG communications menu that visualizes the status about communication networks between multiple ships. The CG label is made *Active,* and a user can select it; when selected the following actions happen:

- The shells of all ships change from opaque to transparent.
- The user is presented with a CG ship communication status panel (menu) that combines the information about three communication networks for each ship - three DDG's and CG's (Figure 28)

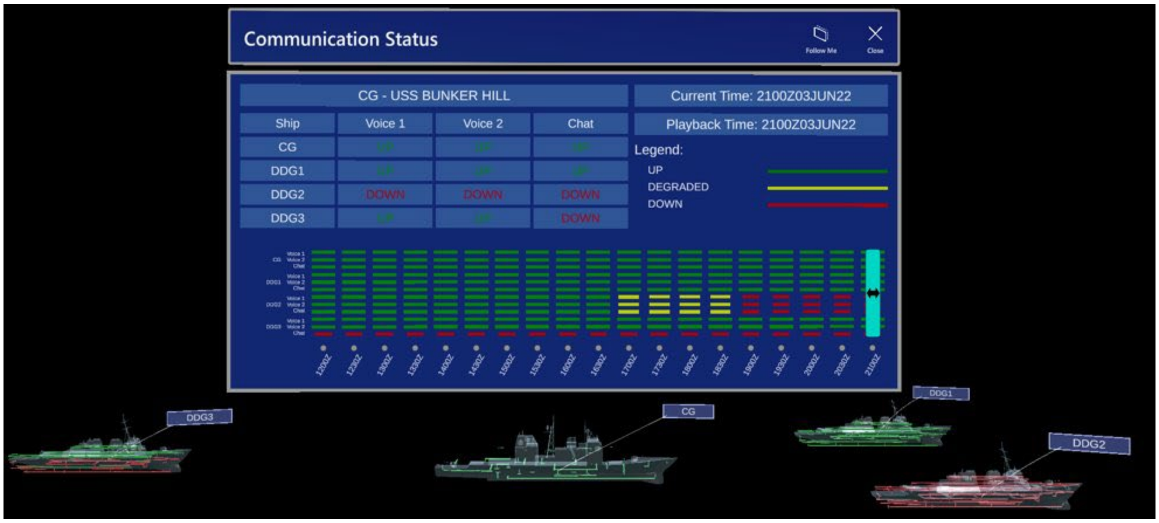


Figure 28. Multi-ship HUD menu.

Unlike Task 1, the CG can disable and enable the labels of each of the three DDGs and display their respective menus, as it can display information containing the details about three DDG's and CG.

Furthermore, the CG and three DDGs can be:

1. Grabbable (selectable),
2. Moved, rotated, and scaled,
3. Have their position reset to the original position, i.e., the position they had at the beginning of Task 2 performance (*Reset* button).

(3) Task 3

Task 3 (Figure 29) has the same functionality as Task 2 consisting of the single and multi-ship menus; however, the specifics of the task are slightly different (details of the task are described in Chapter V).

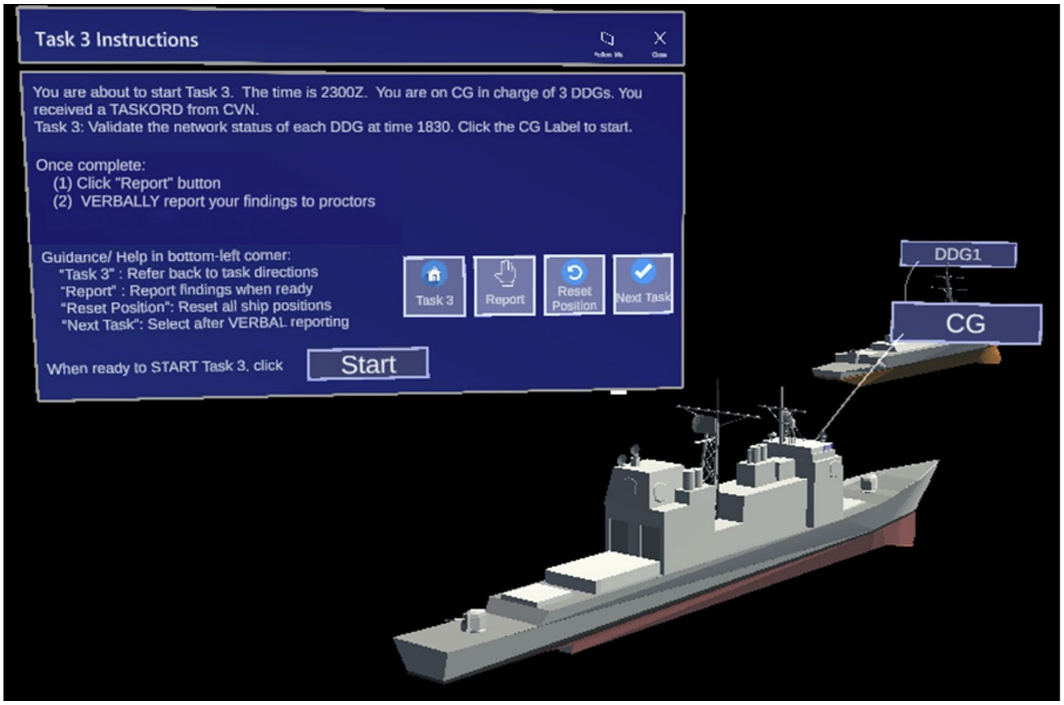


Figure 29. Task 3 Instructions menu.

(4) Task Completion

After all tasks are completed, the user is presented with the completion menu signaling the termination of the study (Figure 30)

Figure 30. Completion menu.

(5) User Interaction and Menu Controls

A user had the ability to control single and multi-ship HUD menus (panel) with the following gestures:

- Select the ship label: Ship's material is initially opaque. When selecting ship label, user hovers the fingers over ship label to select or de-select the label (Figure 31). Once selected, the ship's material becomes transparent, and the communications networks are visible (Figure 32).

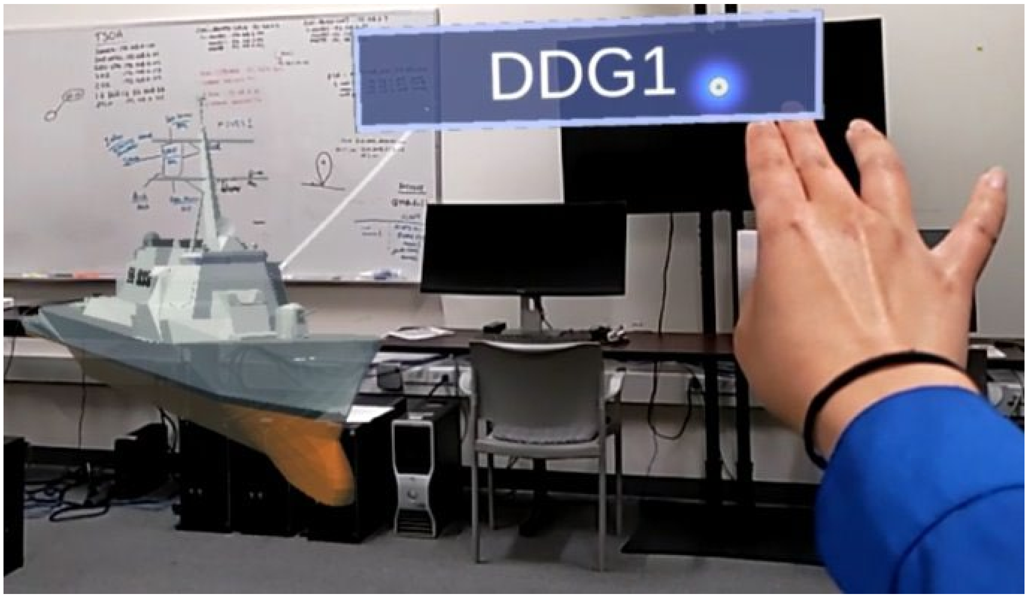


Figure 31. Selection of ship's label.

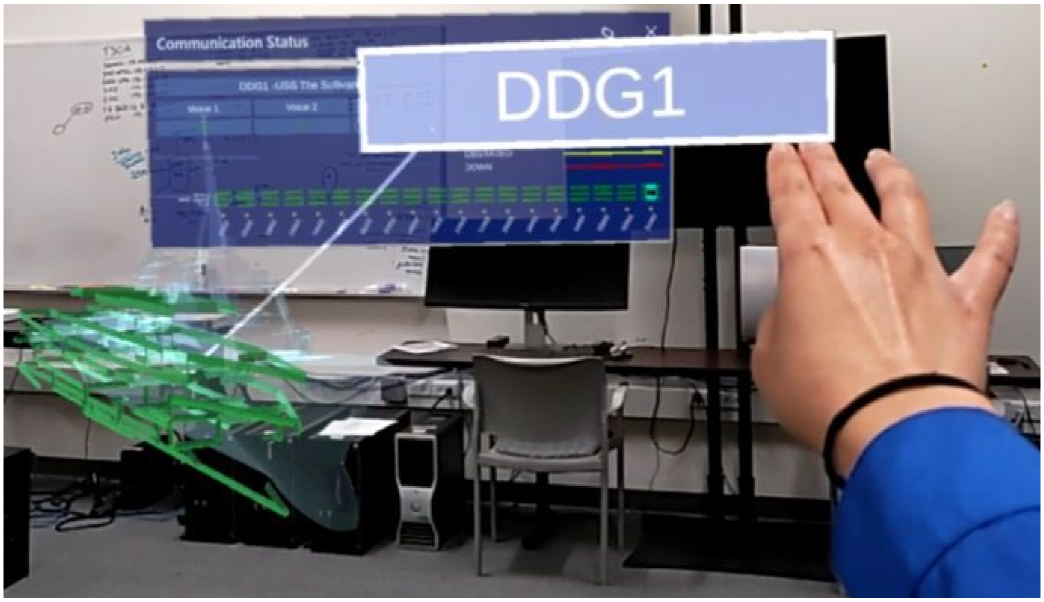


Figure 32. Selected ship's label.

- Grab menus: User's fingers hover over the menu with open hand to signal a selection of that object (step1 shown in Figure 33). Hand with pinched gesture suggests grabbing and selecting the menu (step 2 shown in Figure 34).

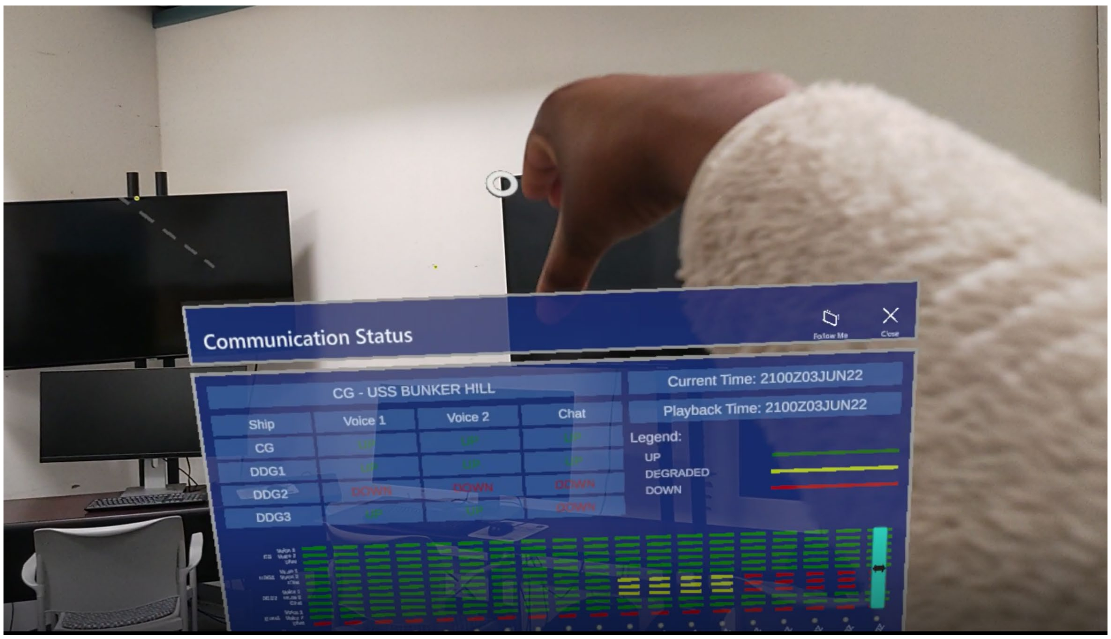


Figure 33. Grabbing a menu, step 1 with hand hovering.

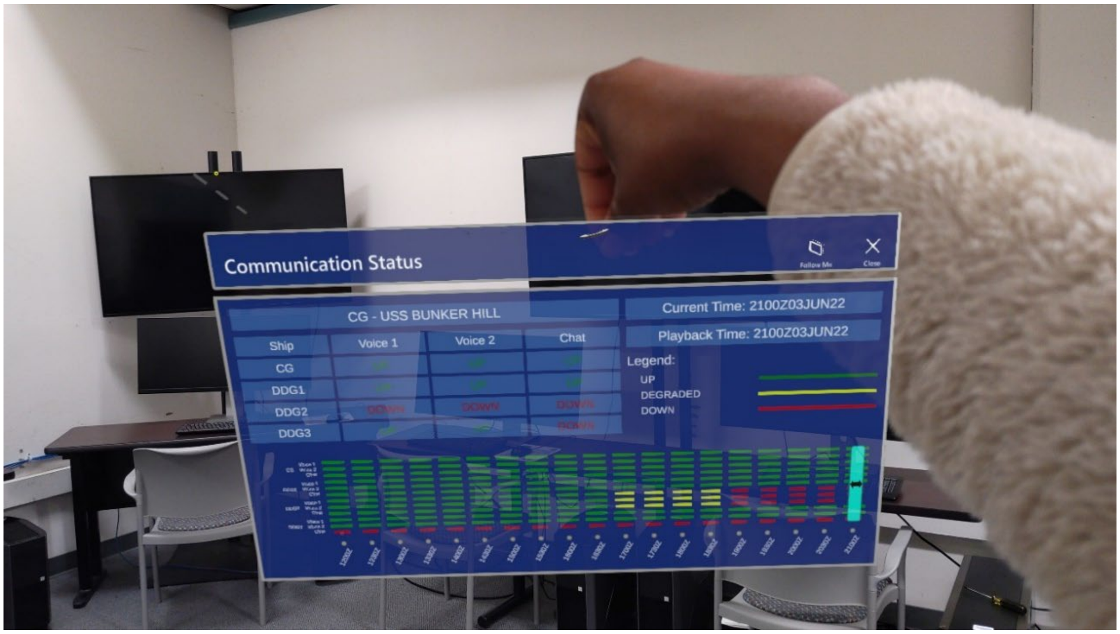


Figure 34. Grabbing a menu, step 2 with pinched gesture.

- Resize ships: User hovers the hands near the object to indicate selection (Figure 35). Pinch gestures initiate resizing of the object that continues until the user ‘releases’ the pinch gesture (Figure 36).

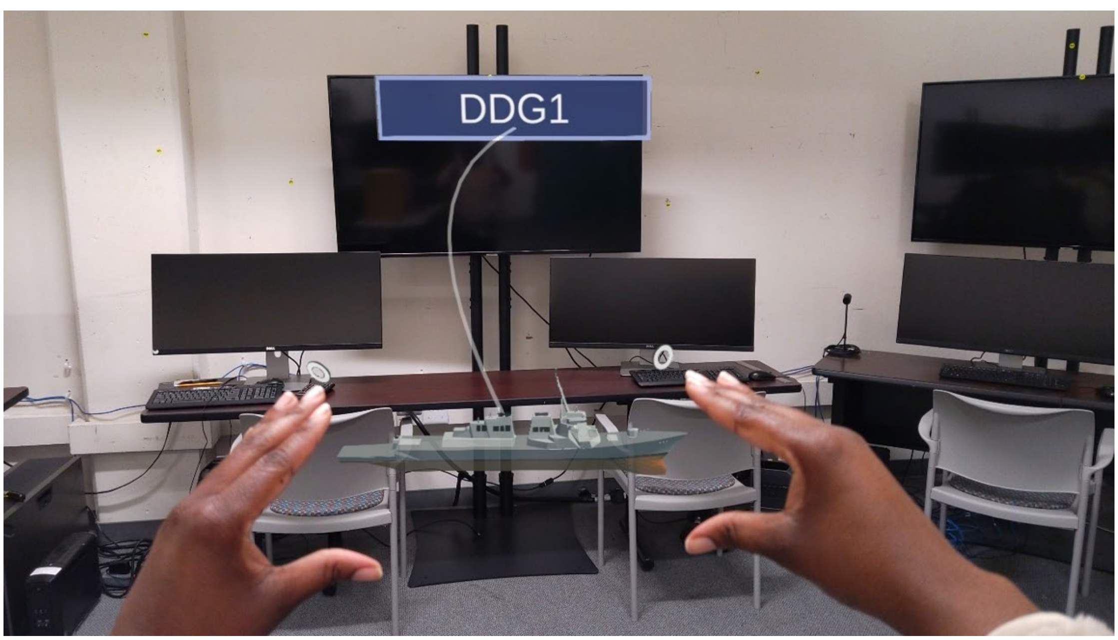


Figure 35. Resizing the object: Hover near the object to select.

Figure 36. Resizing the object: Pinch sides of the ship.

- Using the ray cast action to select objects by ‘point and commit’ gestures: User stretches her open palm in general direction of the object. The ray cast technique with a dashed line is used to indicate potential interest in an object. The end of the ray hovers over the menu and that indicates the ‘point’ gesture (Figure 37). When the thumb and index finger do the air-tap action, the ray cast is drawn with the solid line, and it signals the selection of the object – ‘commit’ gesture (Figure 38).

Figure 37. Menu selection with the ray casting technique: ‘point’ gesture.

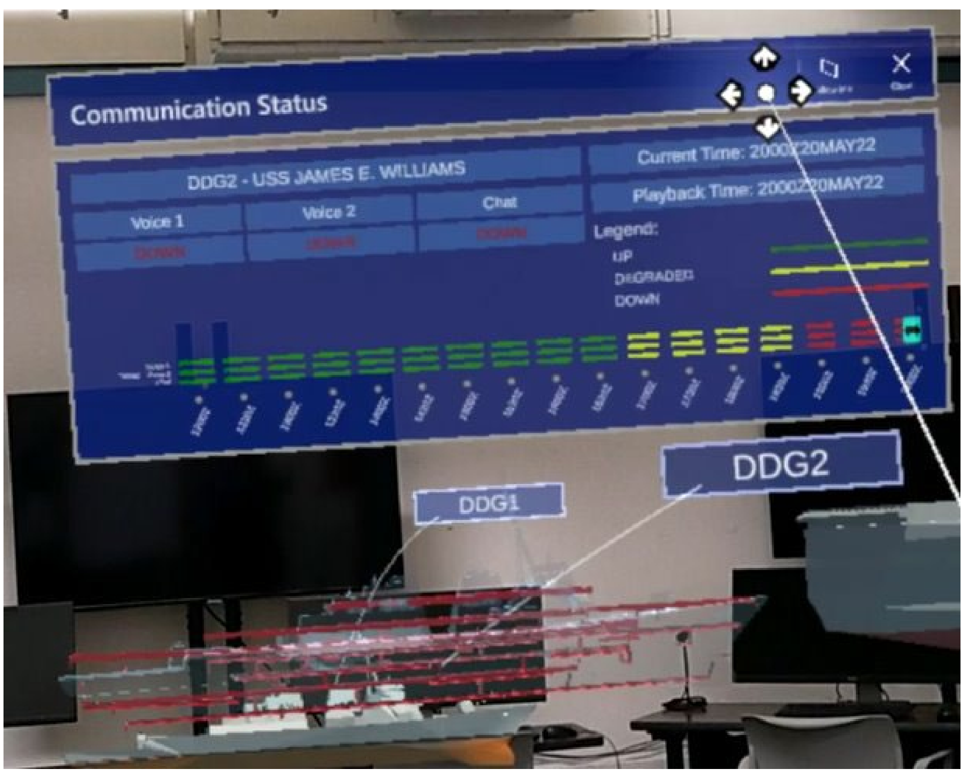


Figure 38. Menu selection with the ray casting technique: ‘commit’ gesture.

- Ray cast technique used to interact with the slider inside the communication status panel (menu): To use the ray casting technique, point to the multi-ship slider within the menu while making sure the end of the ray hovers over the slider button (Figure 39). When the thumb and index finger do the air-tap action (‘commit’ gesture), the ray cast is drawn with the solid line, and it signals the selection of the slider. The color of the slider button changes to purple, and the user can ‘move’ it along the timeline as long as the ‘commit’ gesture is maintained (Figure 40).

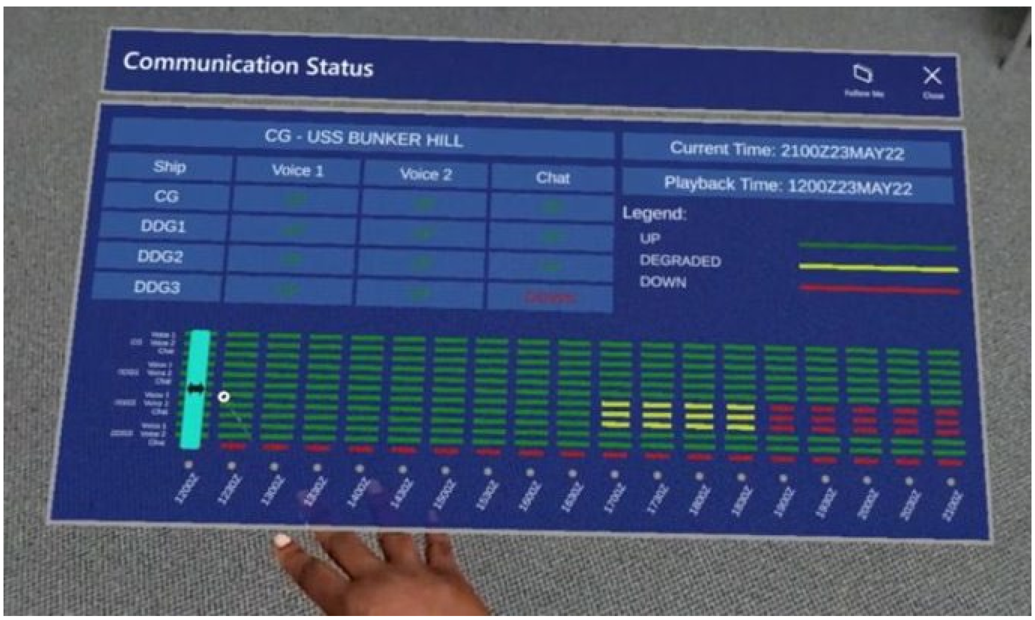


Figure 39. Slider selection with the ray casting technique: ‘point’ gesture.

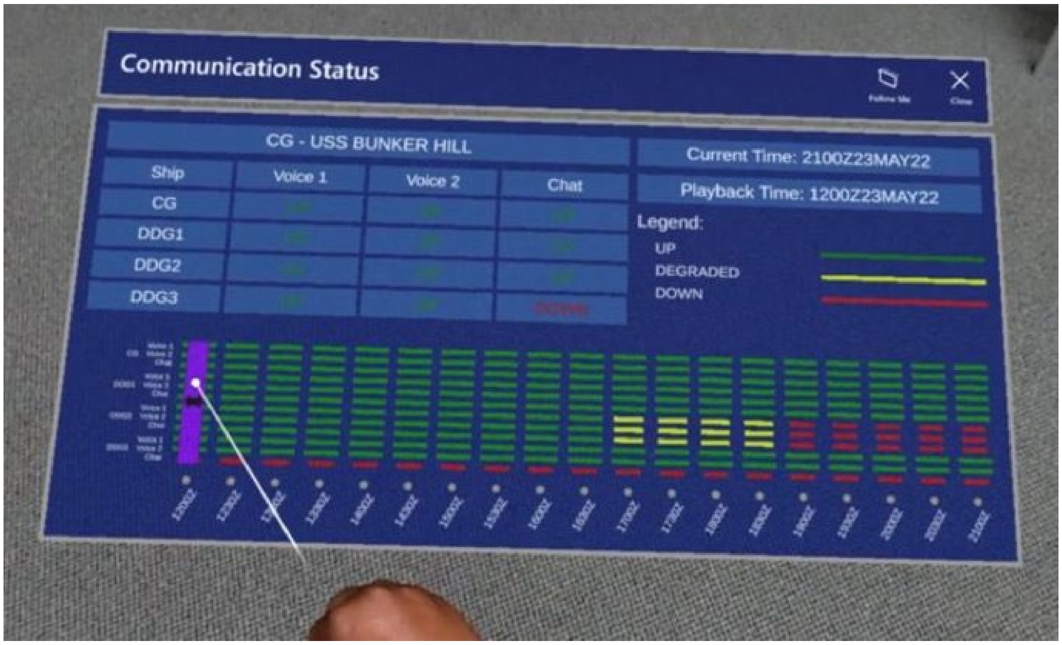


Figure 40. Slider selection and interaction with the ray casting technique: 'commit' gesture.

V. USABILITY STUDY

A. INTRODUCTION

This chapter discusses the results derived from the data sets collected in the usability described in Chapter IV. The objective of this study was to evaluate the effectiveness of the system interface we designed to support decision-making with the PAE solution. The PAE prototype illustrated how the information conveyed in a variety of documents could be transformed into 3D information to allow participants an efficient way of reviewing it and making decisions. A four minute and fourteen second "Short Video Demonstration of PAE Overview_1 of 3," an eight minute and four second "Long Video Demonstration of PAE Functionality_2 of 3," and a "PowerPoint Brief Thesis Overview_3 of 3" can be found in the supplemental section of this thesis for a full visualization of the PAE prototype.

In particular, the PAE prototype visualized different types of communication networks typically found onboard Naval surface vessels and their operational states. The prototype provided a "real-time" representation of the data set and analysis of the same complex data set in an AR-based system while not limiting the current practices and comprehension of complex systems. In addition, the feedback we received from the participants in our usability study helped us generate new ideas and additional ways in which this type of system could benefit the Fleet; we summarized those suggestions in a chapter that reviews future work.

B. INSTITUTIONAL REVIEW BOARD (IRB) PROCESS

Before conducting this study, NPS requires that any research involving human subjects must go through the Institutional Review Board (IRB) process. The following documentation was submitted for the approval of NPS IRB Committee:

1. IRB Application
2. Scientific Review Form
3. Conflict of Interest Disclosure Form

4. Informed Consent Form

5. Recruitment Flyer (Appendix A)

6. Recruitment Email

7. Simulator Sickness Questionnaire (SSQ) (Appendix B)

8. System Usability Scale (SUS) Questionnaire (Appendix C)

9. Demographics Questionnaire (Appendix D)

10. Post-Task Questionnaire (Appendix E)

After submitting the required documentation, we were approved to begin the usability study in May 2022.

C. STUDY DESIGN

1. Physical Environment

The study was held in a controlled environments (laboratory) inside the Modeling Virtual Environments and Simulation (MOVES) Institute at NPS. There were three labels taped to the floor to indicate the starting participants' positions for the two training simulations (H-Tips and MRTK) and the PAE application (Figures 41 and 42).

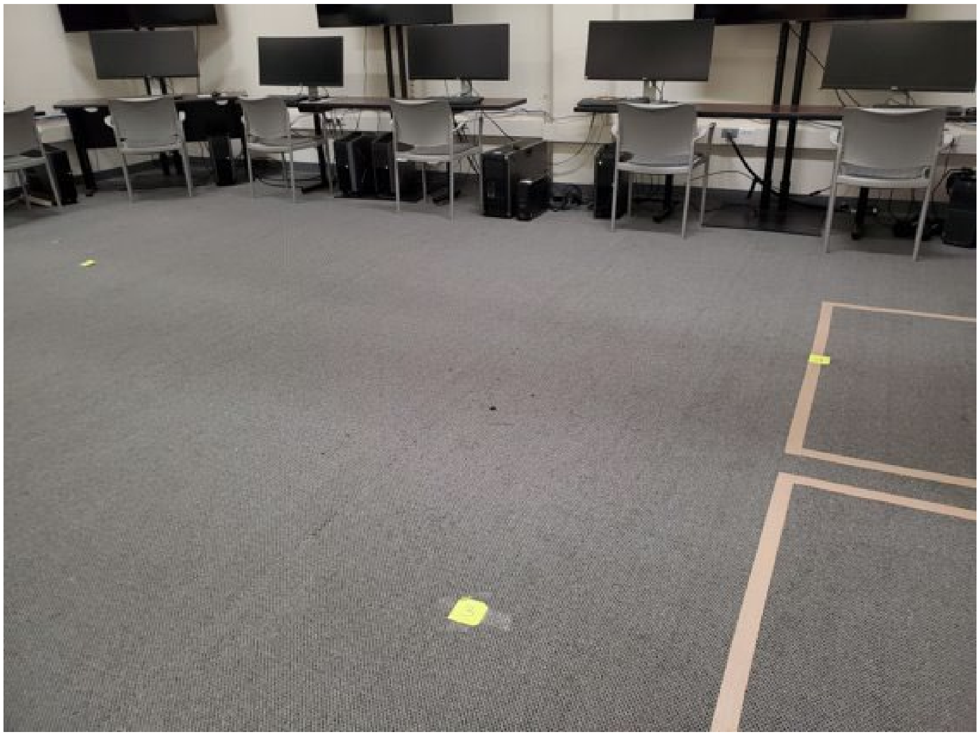


Figure 42. View of H-Tips, MRTK training, and PAE applications without HoloLens 2 headset.

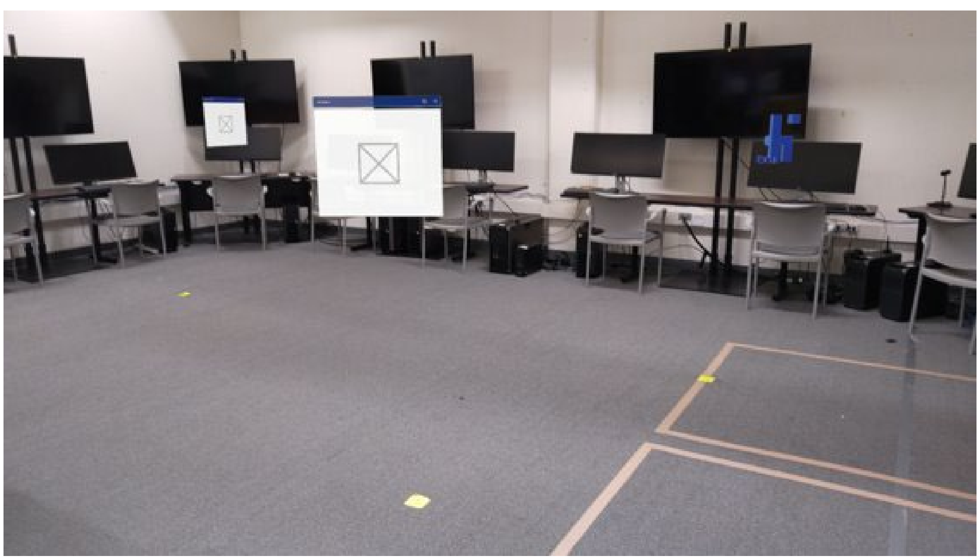


Figure 43. HoloLens 2 view of H-Tips, MRTK training, and PAE applications.

2. Training Environments

Our study participants experienced two training virtual environments. They were introduced to the first training environment called H-Tips (Figures 43 and 44). The purpose of this environment was to familiarize participants within the functionality of the HoloLens 2 headset and user techniques it supported.

Figure 44. H-Tips application.

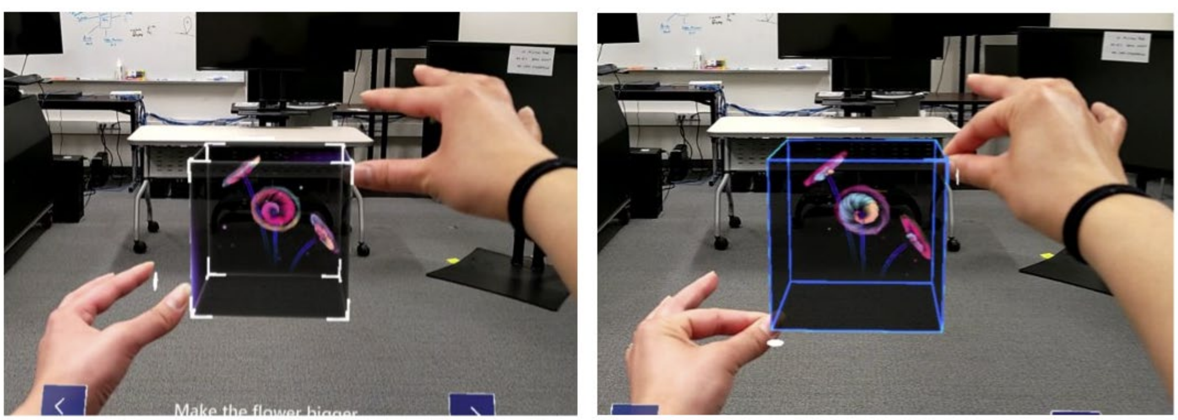


Figure 45. Resizing object in H-Tips.

During the H-Tips training, participants learned how to select, grab, rotate, resize, point, and select the objects using a ray cast interaction technique. The tutorial also allowed HoloLens 2 device to get calibrated on participants' eyes and ensure it was accurately tracking their eye gaze and hands. Next, the participant was asked to use the second training environment called MRTK. User interactions in that environments build upon the training techniques learned in H-Tips and allow participants to practice and use different types of MRTK tools (Figures 45, 46, 47 and 48). Both training environments allowed each participant to acquire the necessary skills that will be needed to execute all tasks in the PAE application.

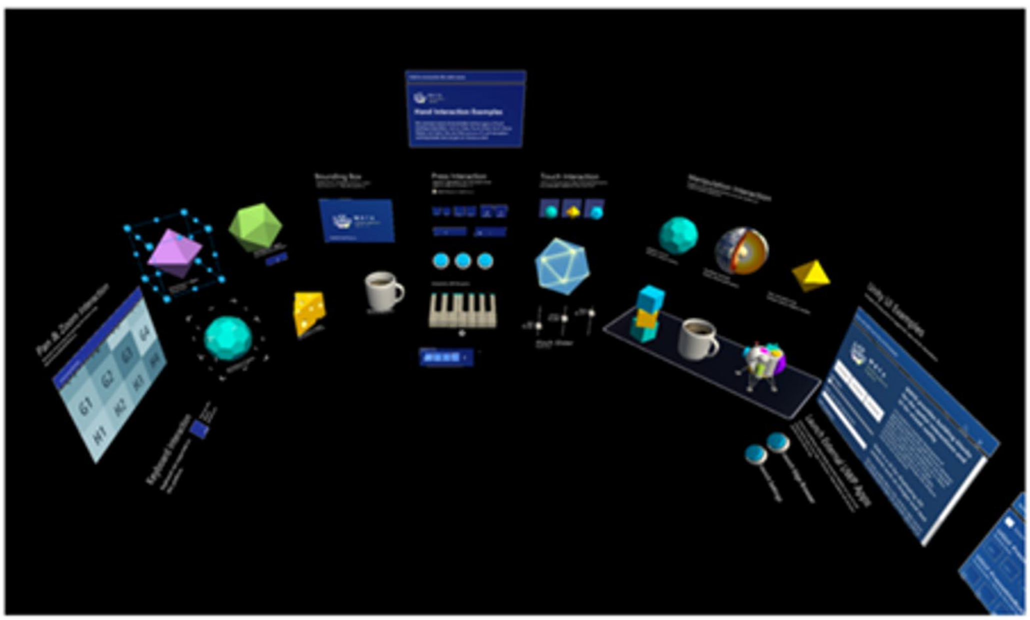


Figure 46. MRTK training environment. Source: [55]

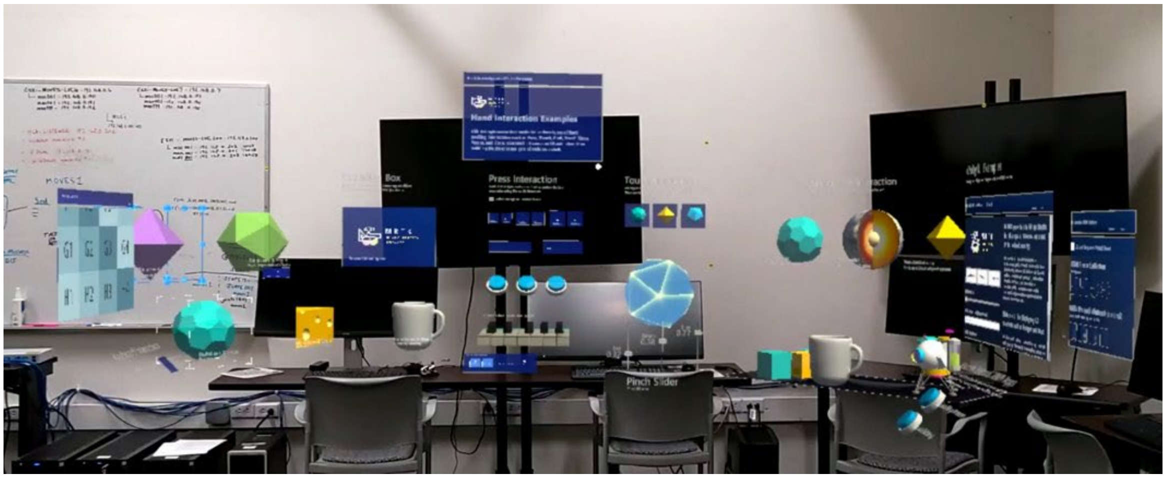


Figure 47. MRTK Training environment as seen by participants in our study

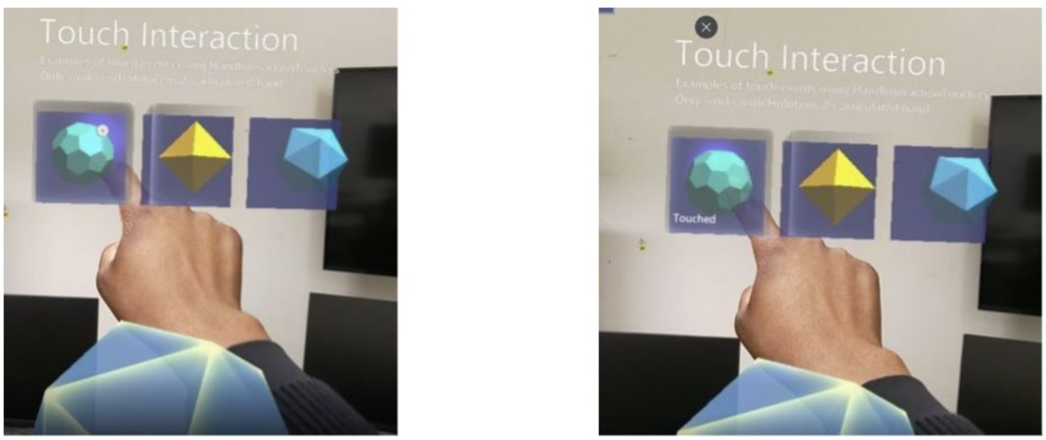


Figure 48. Selecting object in MRTK.

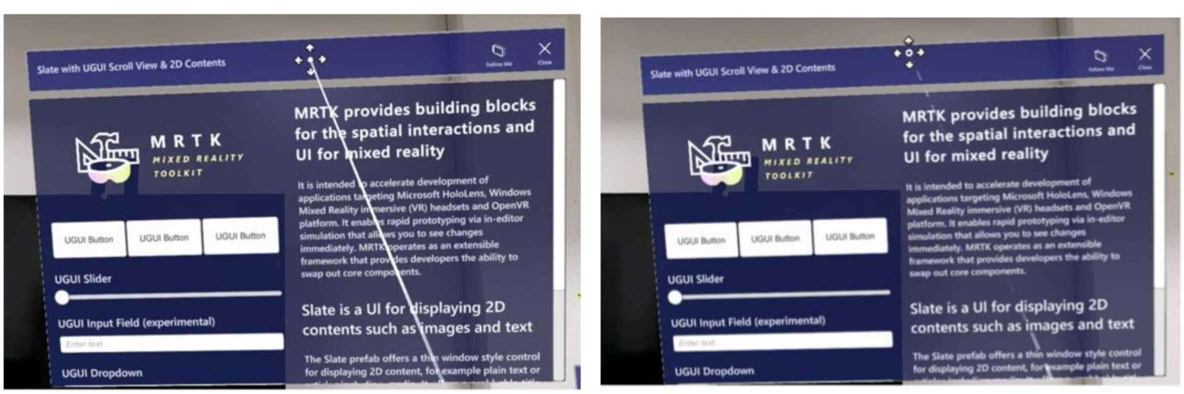


Figure 49. Ray casting selection of the menu in MRTK training.

It was important during this training that the proctors (investigators) had participants move around the space with objects to encourage that they have full mobility to move around the physical space. Another point of emphasis was the user's ability to ray cast select objects that originally are far away from their current position to themselves as another avenue of customizing how they wanted to manipulate the overall environment. Lastly, the participant was introduced to the PAE application to complete three tasks.

3. PAE Tasks

Participants were instructed to perform three tasks within the PAE. The type of participants recruited for our study (their officer designators) allowed us to assume that they understand the basic CoC of a CSG and have prior exposure to traditional methods of visualizing information about communication networks (i.e., COMMPLANs, daily 8, etc.)

After the PAE scene is loaded, the participant is greeted with a welcome menu (Figure 49) and instructed to familiarize herself with the virtual environment; the welcome menu shows a button that allows selection of Task 1. The virtual environment also shows five ships labeled CVN, CG, DDG 1, DDG 2, and DDG 3. After casting a ray or selecting the "Task 1 button," the participant is introduced to a "Task Instructions" menu shown in Figure 50; that panel has detailed instructions on the ship central to the Task 1 described in Chapter IV. The menu provides information about four options that are available via anchored menu bar (menu is anchored in the same position for each task): return to task instructions, signal the reporting of the task results, reset the environment, and move to the next task.

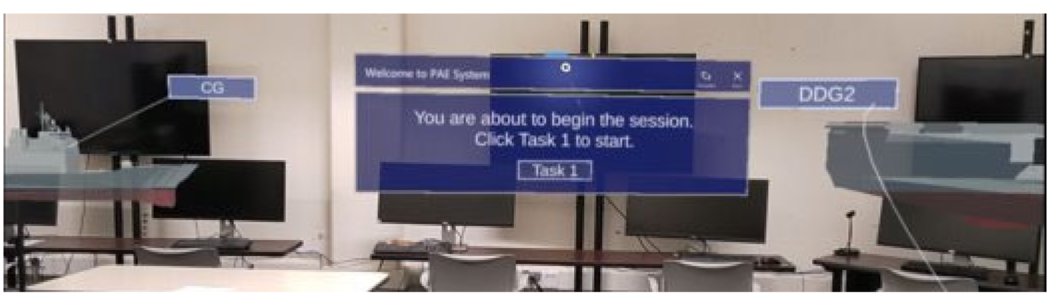


Figure 50. PAE Welcome menu.

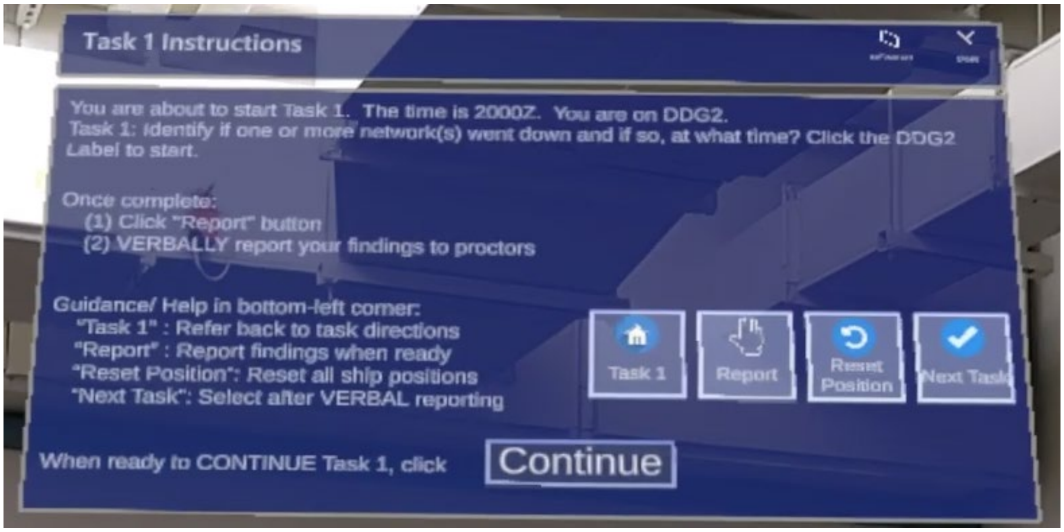


Figure 51. Task1 instructions.

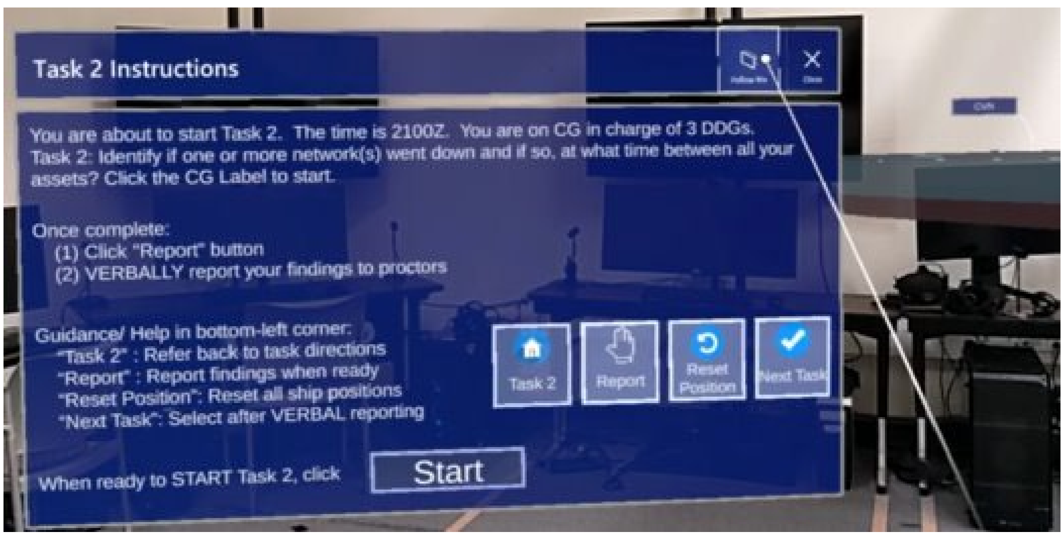


Figure 52. Task 2 instructions.

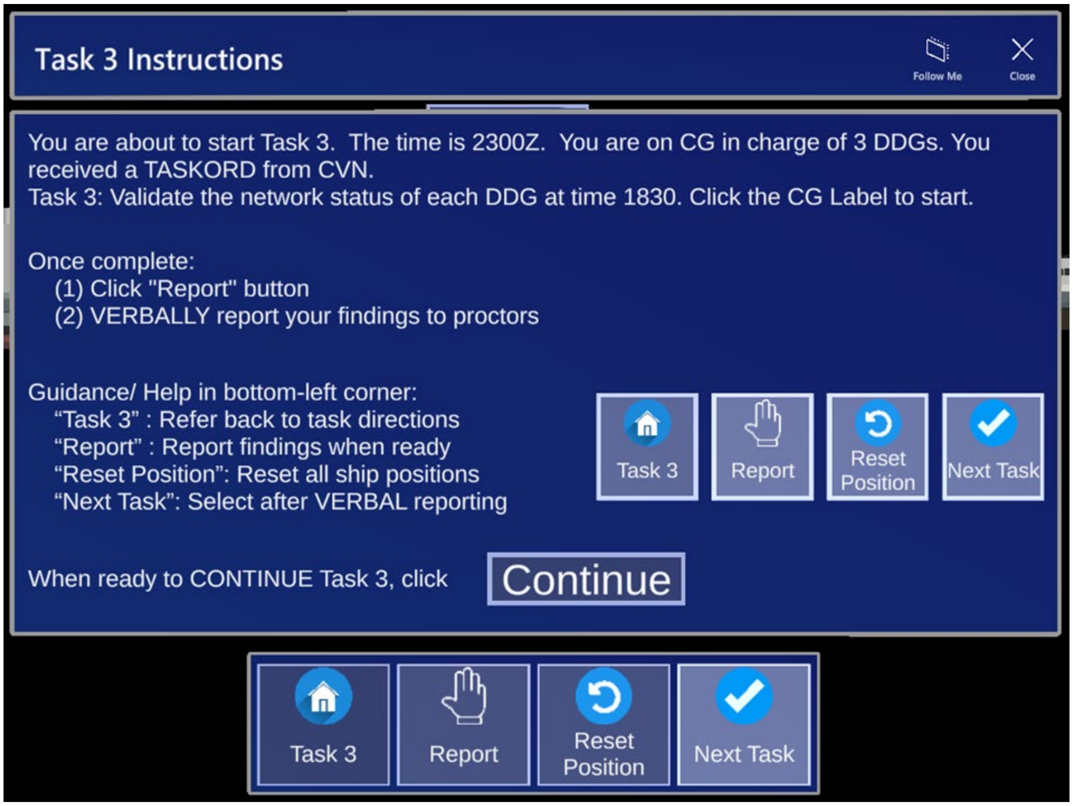


Figure 53. Task3 instructions.

The specifics of each task are:

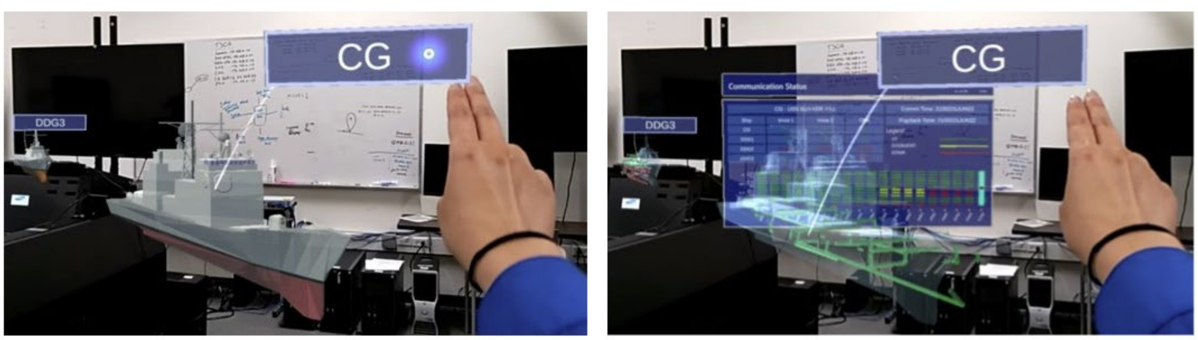
(1) Task 1 Instructions (Figure 50): You are about to start TASK 1. The time is 2000Z. You are on DDG2. TASK 1: Identify if one or more network(s) went down on DDG2 and if so, at what time?

(2) Task 2 Instructions (Figure 51): You are about to start TASK 2. The time is 2100Z. You are on CG in charge of 3 DDGs. TASK 2: Identify if one or more network(s) went down and if so, at what time between all your assets?

(3) Task 3 Instructions (Figure 52): You are about to start TASK 3. The time is 2300Z. You are on CG in charge of 3 DDGs. You received a TASKORD from CVN. TASK 3: Validate the network status of each DDG at time 1830.

Participants can select only DDG 2 in Task 1. For tasks 2 and 3, the participant has the ability to select every label except for the CVN. When a label is selected, the ship becomes transparent, showing three different types of communication networks (Figure 53 and Figure 54) and a communication status menu appears for that ship. The only ship that has the ability to show multiple ships on its Communication Status menu is CG (Figure 54).

Figure 54. Three different types of communications inside DDG1.



Visual information before selecting the ship label (left), and visual information after ship label is selected (right).

Figure 55. Selecting label of CG ship to activate Communication Status menu.

As shown in Chapter IV, participants can:

- Select label

- Grab and move the menu panel
- Point to and select the menu items
- Point to and select a slider on menu
- Resize each ship
- Reset the entire environment

After a participant reaches the "completion" menu (Figure 55), the scenario is complete; that marks the end of the study for the participant.

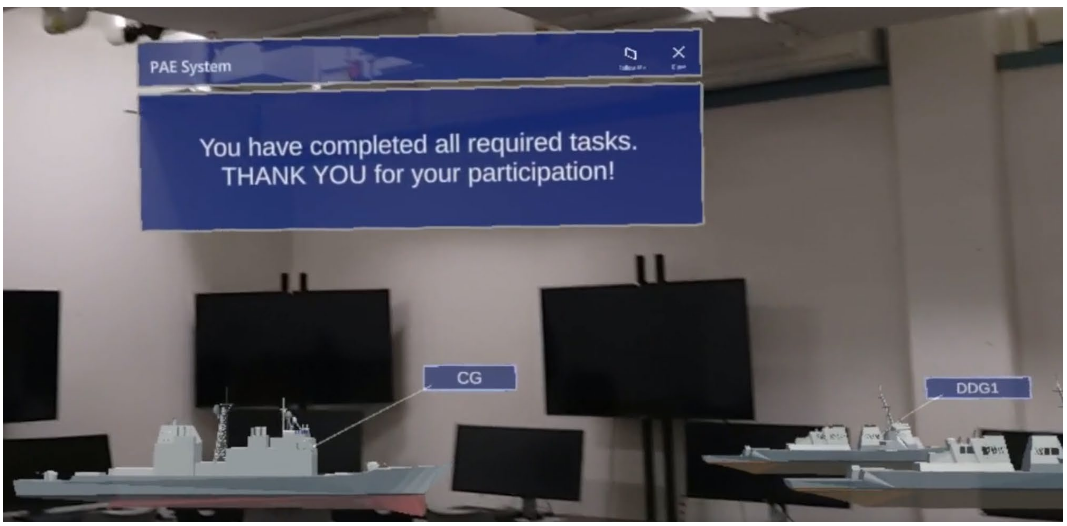


Figure 56. Completion Menu of PAE using HoloLens 2.

4. Collection of Objective Data Set

The objective data set is a collection of information reported by the system. Each information is based on the participant's interaction with the menu items and objects in the PAE. When the participant selects the "Task 1" button on the welcome menu (Figure 49), that interaction is recorded in a system event log file that has a format of an excel data file. After signaling the start of the "Task 1" by selecting that button, any interactions with the menu items and objects within the PAE is logged until the participant exits the application. The event log is saved once a participant reaches the completion menu (Figure 55).

The system event logs contained the following data sets:

(1) Number of seconds since the application started

(2) Time stamp of every task start and task end

(3) Time stamp of every menu selection

(4) Time stamp of the start and end of each object manipulation (translation, rotation, and scaling) and ID of the object that was manipulated

We combined the data logs for each participant to make summative information and analyze the data collected from all participants.

5. Collection of Subjective Data Set

Subjective data set was collected by using a set of questionnaires printed on the paper; participants were asked to fill the information by hand. We entered information from all participants to an excel spreadsheet for further analysis.

The subjective data were captured by using following questionnaires:

(1) Baseline, pre-task, and post-task Simulator Sickness Questionnaire (SSQ) [67]

(2) System Usability Scale (SUS)[68]

(3) Demographics questionnaire

(4) Post-Task Survey

Post-Task verbal comments from participants were recorded if participants wanted to ask any question or comment on their performance; however, we did not ask any questions beyond pre-approved questionnaires.

D. PROCEDURE

During the study, the participants used the H-Tips and MRTK training environments; it took about 15 minutes to complete both training simulations with guidance from the investigators as needed. That was followed by three tasks using the PAE prototype. Time to complete each task was unlimited and this time the proctors (investigators) did not provide any guidance unless deemed necessary. Participants could only rely on the instructions within the PAE to accomplish each task. Participants were instructed to read aloud, vocalize their answers to each task's question, and tell the proctors what they are thinking; this was all captured on a video that was analyzed.

The following procedure was used for each participant:

(1) Participant was greeted and was given a short brief about the study (2 minutes).

(2) Informed consent (5 minutes)

(3) Baseline simulator sickness questionnaire (SSQ) (2 minutes)

(4) Training: Familiarization with HoloLens 2 headset and user interface. Participant is asked to complete training using H-Tips and MRTK training environments; that included information about the techniques for reducing cybersickness symptoms. (15 minutes)

(5) Pre-experiment simulator sickness questionnaire (SSQ) (2 minutes)

(6) Instructions for the main experiment (2 minutes)

(7) The main experiment: three tasks (30 minutes).

(8) Post-experiment simulator sickness questionnaire SSQ (2 minutes)

(9) Post-task survey and SUS questionnaire (4 minutes)

(10) Demographics questionnaire (2 minutes)

(11) A short study debrief, with an opportunity to ask questions (5 minutes).

E. PARTICIPANTS

The study involved 27 U.S. Navy Officers. Originally there were 29 participants; however, one of the two HoloLens' failed to connect to the Microsoft Remoting app to retrieve two event log files resulting in the exclusion of the data sets for those two participants. That limitation will be further discussed in this chapter. To ensure there was a diverse pool of officers for the study, we advertised for the following designators: current and former Surface Warfare Officers (SWOs), Engineering Duty Officers (EDOs), Cryptographic Warfare (CW) Officers, and Information Professional (IP) Officers.

Advertisement of the study was conducted using email correspondence, a recruitment flyer (Appendix A), and personal communication with fellow students.

1. Demographics Questionnaire

The total of 27 participants took part in the study; eight were female and 19 were male participants (Table 3).

Table 3. Participants' gender.

	Gender
Female	8
Male	19
TOTAL	27

The ranks of the participants ranged from O-2 (LTJG) to O-5 (CDR), with the majority of the participants having prior shipboard experience, as shown in Figure 56. The participants' years of service ranged from 4 years to 21 years, with an average of 9 years (Table 4).

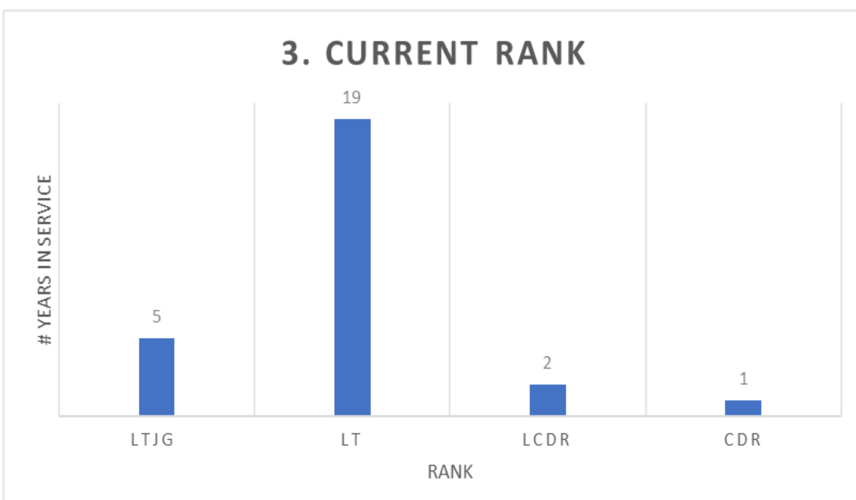


Figure 57. Participants military ranks.

Table 4. Analysis of participants' years of service.

	Years of service
Average	9
Min	4
Max	21
St. Dev.	4.08

As shown in Figure 57 most of the participants were SWOs (eight participants). Five participants were EDO, six were IP, five were CW, and three were in 'Other' category (two were Intel Officers who are qualified Information Warfare Officers, and one former SWO who transferred into the Foreign Affairs Officer community). It is of note that some participants were former SWOs who transferred into other communities: EDO, IP, CW, or other category; this means that they had SWOs skills as well.

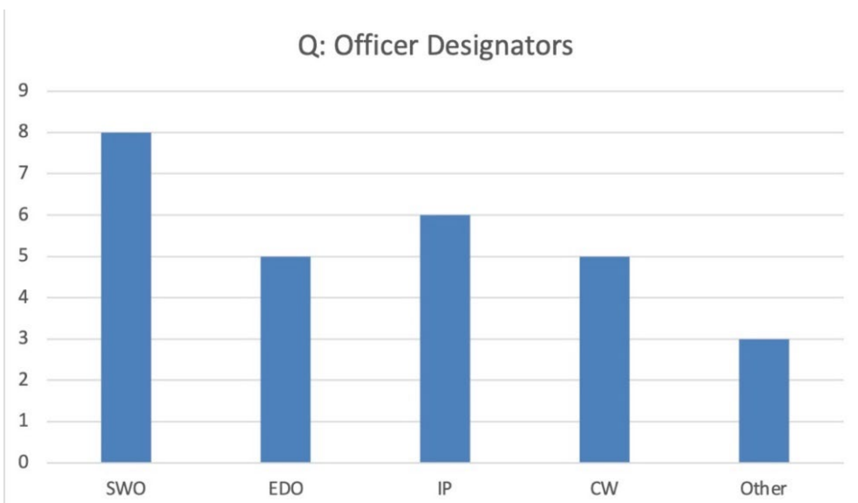


Figure 58. Participants' officer designators.

Also, participants' experience with AR and VR varied, with the majority of participants being exposed to some type of VR environment, as shown in Figure 58. Data collected in the demographics questionnaire suggest that eight participants never used VR or AR HMDs. A total of 11 participants experienced VR and AR HMDs for personal reasons only, eight participants used VR or AR HMDs to meet Naval or work-related requirements, and only one participant used VR or AR for both personal and work purposes

(Figure 59). The question related to prior use of VR or AR HMDs allowed us to examine if prior exposure to those technologies could have an impact on their task performance in the study when compared to the results of participants who have never tried those systems.

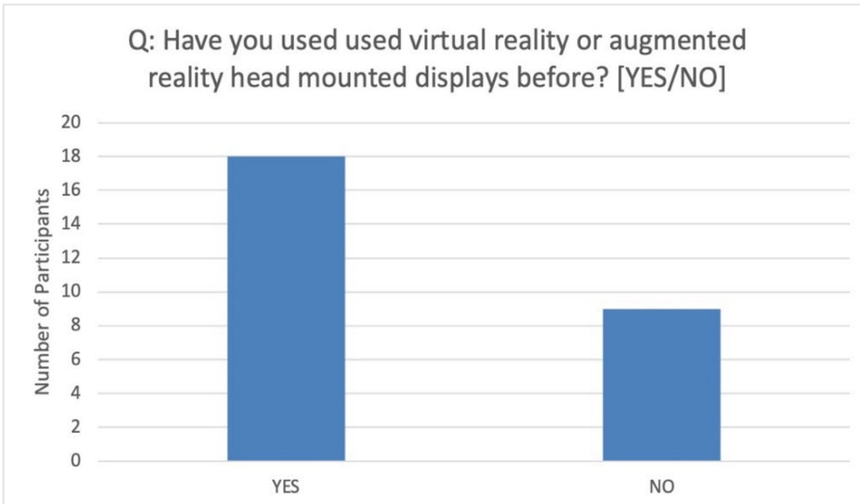


Figure 59. The number of participants that have used VR or AR HMDs before.

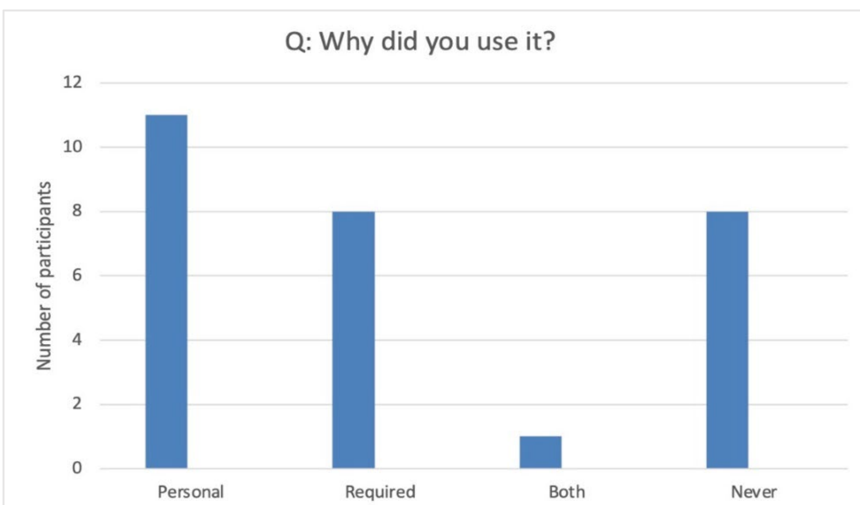


Figure 60. The purpose of VR or AR HMD use.

2. Demographics Questionnaire: Experience

From the demographics data set collected from 27 participants, we were able to analyze the prior experience participants had with communication networks onboard a surface ship. Another question was related to the extent their interaction was onboard a ship and if they played a role in network operations (NETOPS) planning. The data suggested that only two participants had never interacted with communication circuits and/or networks on a surface vessel before, as seen in Figure 60. Even though they never interacted with communication networks onboard a ship, they were able to tell us how the same networks and communications were visualized traditionally.

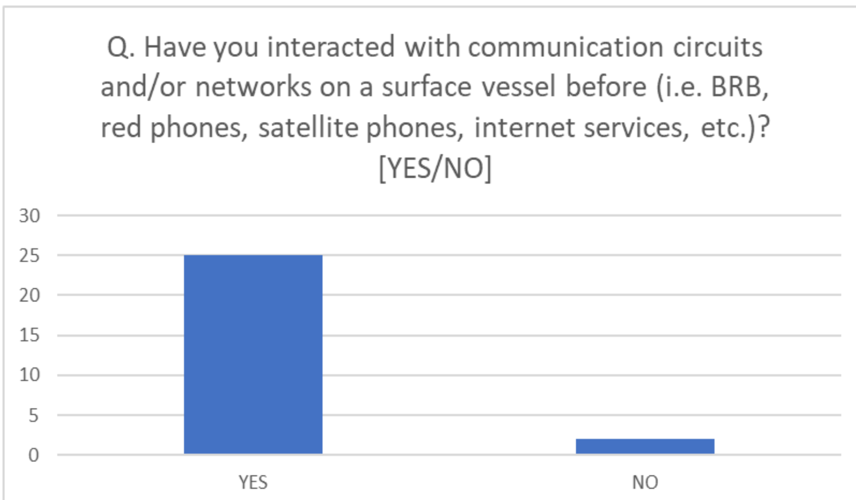


Figure 61. Number of participants who interacted with communications or networks.

Figure 61 shows that 63% of individuals participated in NETOPS decision-making, which encompassed generating communication plans (COMMPLAN), daily 8 reports, or reporting the status of networks and communications for deconfliction.

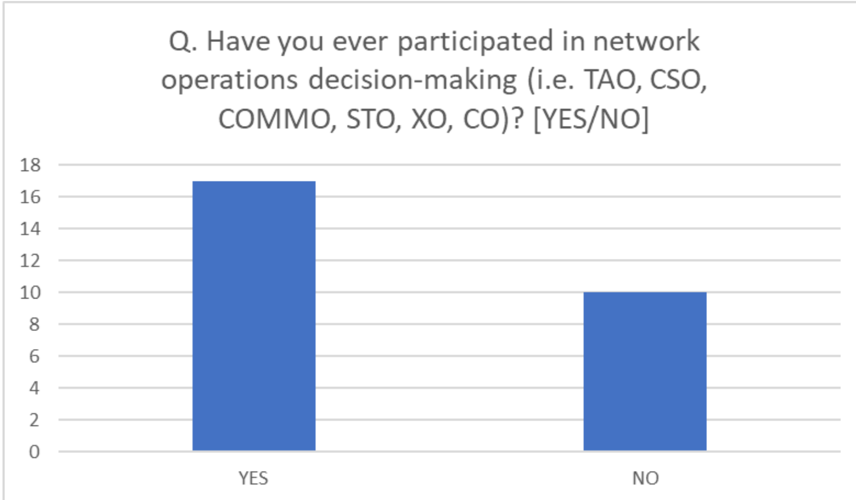


Figure 62. Number of participants who have participated in network operations decision making

F. RESULTS

1. Objective Data Set

At the start of the scenario, the participant is greeted with a welcome menu (Figure 49) to begin task 1. After selecting the "Task 1" button on the welcome menu, the participant is introduced to the task 1 instruction menu to complete task 1.

The analysis of the event logs, Task 1 took the longest amount of time compared to other two tasks (Figure 63). We suspect that the length of that time is a result of participants' need to take their time to fully understand the PAE environment, understand the details of the task and then apply the input techniques they learned in H-Tips and MRTK training environments. On average, Task 1 took four minutes to complete (average was 4.09 min, minimum (min) was 1.87 min, maximum (max) was 7.67 min, and standard deviation (StdDev) was 1.21 min), with the fastest time being almost two minutes. In case of the individual who completed the task so quickly, it was found later on that the participant read the instructions very quickly but did not fully understand what to do; the individual was purely focused on completing each task as quickly as possible. Each task was designed to build from the previous one - there was a great deal of familiarity once they completed the first task, and the following task added more complexity. Both characteristics resulted with Task 2 averaging three minutes (average was 3.44 min, min was 1.52 min, max was 5.06 min, and StdDev was 0.84 min), and Task 3 averaging a little under three minutes (average was 2.84 min, min was 1.36 min, max was 4.96 min, and StdDev. was 1.07 min). Typically, participants were able to identify and complete each task at a faster rate from the prior task since the instructions were very similar across the tasks and the functionality embedded in the scene were the same.

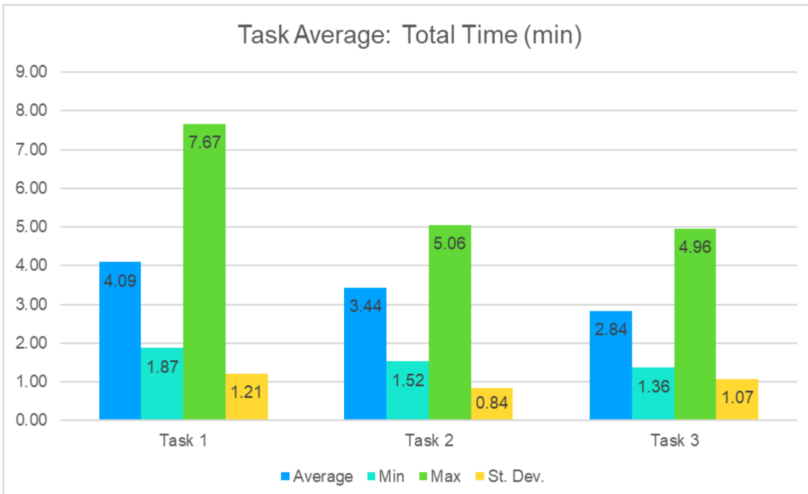


Figure 63. Participants' time on task for the three tasks in the PAE.

The availability of resources to be interacted with increased as a participant progressed through the tasks. Figures 64, 65, and 66 show the average number of times an object was moved (translation), rotated, or scaled during each task. For Task 1, on average, participants moved, rotated, or scaled an object about four times; that number goes down in Task 2 and Task 3. We suspect that the average number of object manipulations in Task 1 was higher when compared to Task 2 and Task 3 because in Task 1 participants were just introduced to a new environment, and it took a while to understand the objects in the space – that process also included manipulation of the same objects. As a participant progressed through the tasks, the number of object manipulations decreased. The participants' familiarity with the scene and the tasks were likely the reason for the reduced number of object manipulations (Table 5).

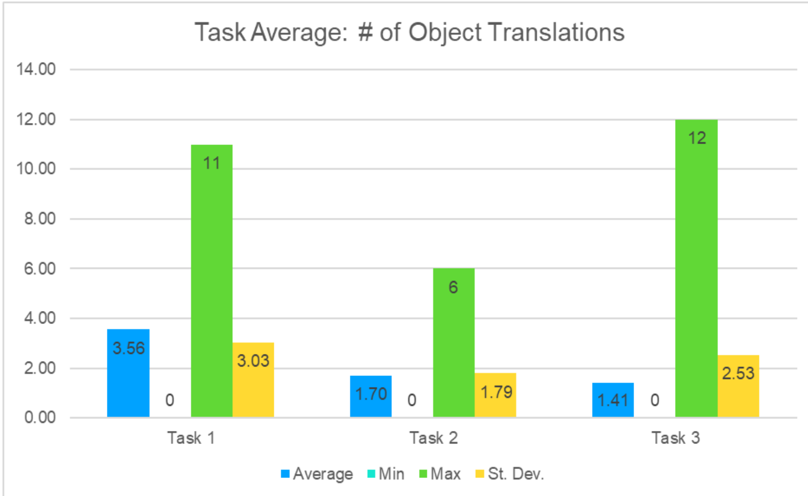


Figure 64. Analysis of the number of object translations in each task.

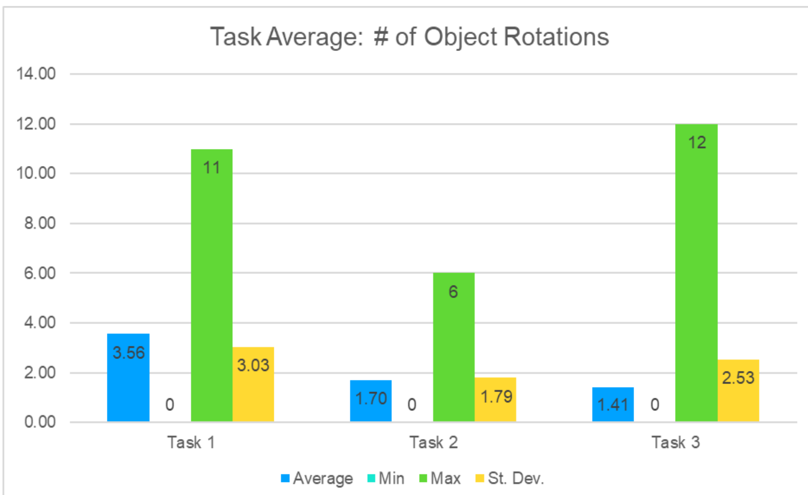


Figure 65. Analysis of the number of object rotations in each task.

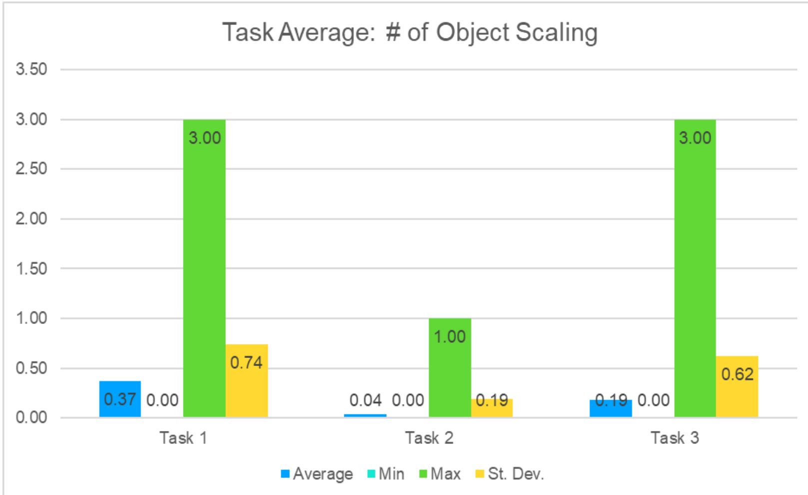


Figure 66. Analysis of the number of object scale operations in each task.

We also noticed that the size of the FOV in HoloLens 2, i.e., its limited size, may have contributed to a lower number of object interactions. We observed that participants were hesitant to intentionally move their heads around or physically move around the space. Typically, participants would only interact with objects positioned within their direct FOV and did not look around too much. That behavior is quite similar to normal usage of mobile devices that participants use daily, e.g., cellphones, tablets, and desktops. This type of phenomenon will need to be examined more thoroughly in future studies.

In summary, every participant moved at least one object in all three tasks. The maximum number of translations executed by an individual in Task 1 was 11, in Task 2 that was six, and in Task 3 was 12 (those were different individuals). We can only speculate that the participants with the highest number of translations either understood the full range of interactions they could achieve in the PAE system and wanted to explore it, or they needed time to understand the environment and experimented with object manipulations out of curiosity and a desire to complete the task correctly.

Table 5. Total number of object manipulations

	Total number for all participants
Task 1 translations	96
Task 1 rotations	95
Task 1 scale op.	10
Task 1 total	**201**
Task 2 translations	46
Task 2 rotations	46
Task 2 scale op.	1
Task 2 total	**93**
Task 3 translations	38
Task 3 rotations	38
Task 3 scale op.	5
Task 3 total	**81**
TOTAL translations	180
TOTAL rotations	179
TOTAL scale op.	16
TOTAL manipulations	**375**

As shown in Figure 67, the average number of translations, rotations, and scale operations was about 14. Scaling was relatively lower than translations and rotations because participants rarely resized the ships. Furthermore, most participants commented that they had no reason to manipulate the objects since all the information regarding the ships' degradation of communication networks was well organized on the Communication Status menus; thus, the information was easily found, and the tasks were not difficult to complete.

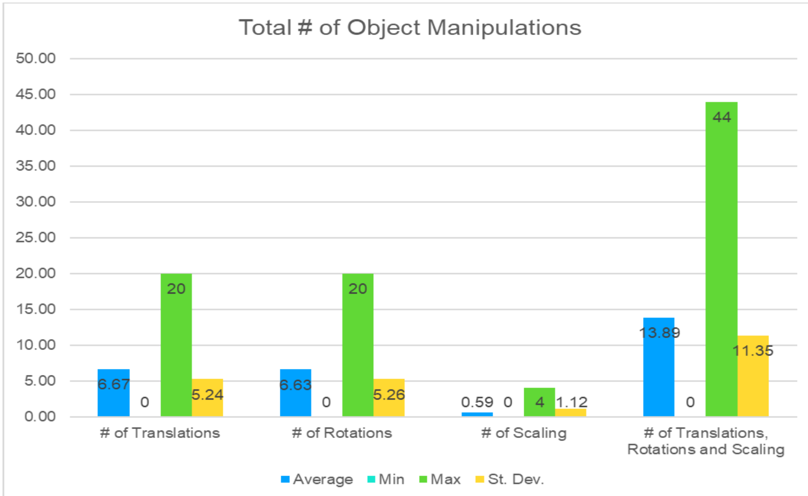


Figure 67. Analysis of the number of object manipulations in each task.

Figure 68 shows the amount of time participants had a panel with task instructions activated and available for their study. Between the three tasks, the average time was almost 4 minutes. Task 1 instructions took the most time, as we originally anticipated. As the participant progressed through the tasks, time they needed to study instructions decreased - the information on the instruction menus were the same except for small specifics related to each tasks.

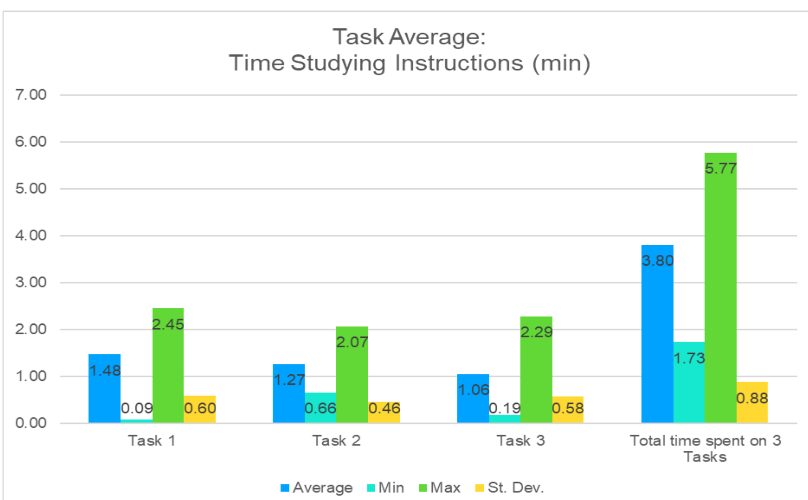


Figure 68. Average time tasks' instructions were activated and available for study.

The average amount of time a participant had Communication Status menu activated and was able to study it, spent reading the communications menu for Task 1 and Task 2 was less than 1 minute, but for the Task 3 was one minute (Figure 69). We suspect that participants took the most time to read Task 3 Communications Status menu to verify the task was well understood before selecting the Report button - this task required that they interact with the status slider and position it back in time to validate the networks' status. Our data suggested that it took no more than one minute to study the information relevant to the Communication Status in Task 1 and Task 2; however, manipulation with the slider object within their FOV in Task 3 caused that time to increase.

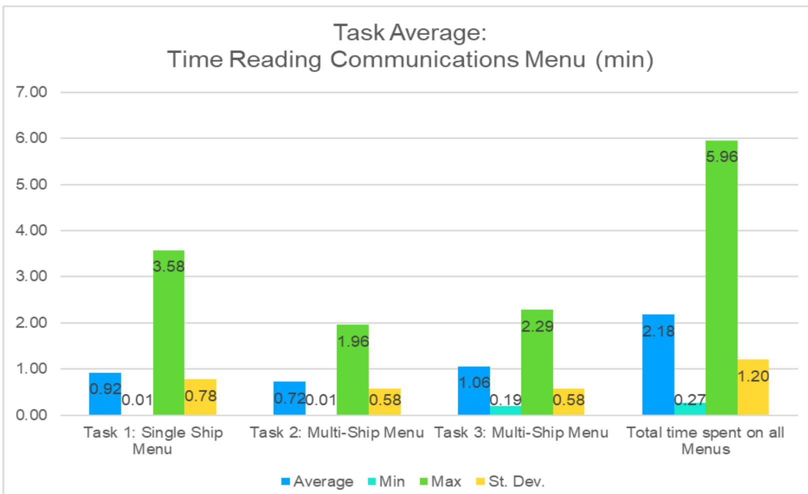


Figure 69. Average time reading tasks' Communication Status menu.

The maximum number of times a participant referred back to Task 1 instructions was three times and two times for Task 2 and Task 3 (Figure 70). From our analysis of videos that were recorded for each individual, participants who referred back more often did not comprehend the instructions and thus were moving too fast or they referred back to instructions to ensure they met all the objectives.

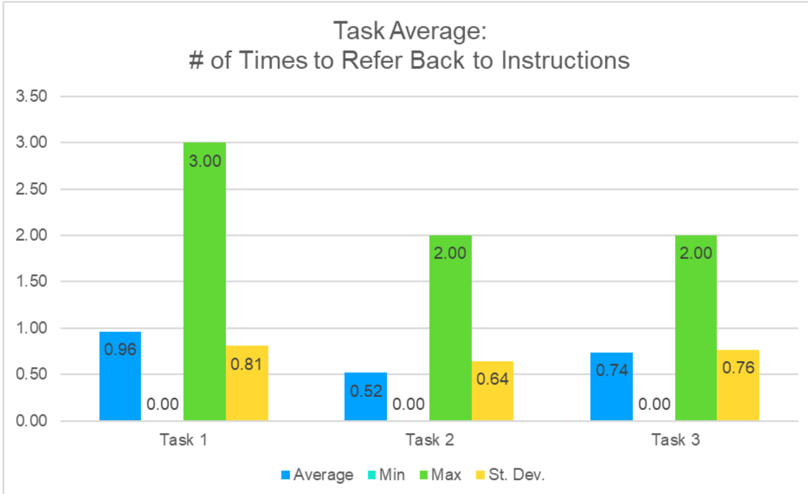


Figure 70. Number of times a participant referred back to the instructions.

Overall, the average time to complete all three tasks was 10 minutes (Table 6 and Figure 71). It is important to note there were three outliers during the study. One participant had the fastest time for the entire study was 8 minutes, followed by 9 minutes, and the longest participant took 17 minutes from when the application first opened to the completion menu. We believe the participant with the fastest time was focused on quickly completing the tasks instead of taking the time to understand the functionality while the participant you took 17 minutes emphasized exploring everything in the environment to ensure all potential avenues were met to complete the tasks.

Table 6. Total times spent on each task

Subjects	Time spent in all tasks (measured in minutes)
1	6.87
2	10.43
3	13.95
4	11.26
5	8.80
6	9.82

Subjects	Time spent in all tasks (measured in minutes)
7	13.06
8	12.09
9	6.40
10	9.57
11	8.08
12	10.07
13	10.35
14	9.78
15	9.41
16	10.39
17	12.13
18	9.88
19	13.63
20	7.61
21	13.58
22	9.80
23	11.10
24	9.02
25	7.69
26	11.79
27	10.41
Average	**10.26**
Min	**6.40**
Max	**13.95**
StdDev	**2.01**

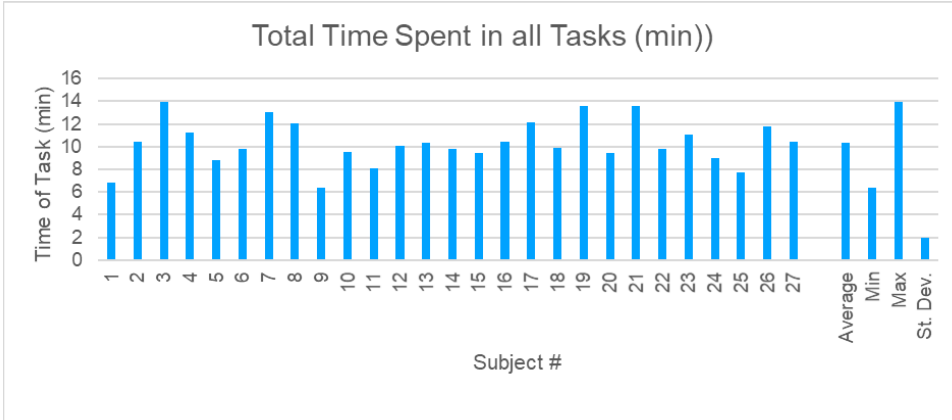


Figure 71. Total time spent in all tasks (measured in minutes).

Finally, the task performance collected during the study – the verbal reports provided by each participant for each task – confirmed that almost all participants were able to complete each task. There were only three participants who provided incorrect answers for Task 3; however, all three participants were able to read the information from the ship menu. This is a unique testimony of the simplicity of data representation and the ease with which all participants were able to execute all tasks.

2. System Performance

We examined the overall system performance that was manifested during our study. It was important to know the information about the resulting frame rate during training segment and task executions; the high frame rate is needed for smoother smoothed navigation and interaction with scene objects. The HoloLens can refresh 240 times a second providing the target or optimal frame rate of 60 Frames Per Second (FPS) or 16 milliseconds. By improving the overall system performance (i.e., increasing the frame rate), the participant has the opportunity for an optimal experience when utilizing the HoloLens. While there are many factors that can impact user performance, a significant potential bottleneck is the size of the scene that needs to be rendered. The ship models in our virtual scenes could be densely tessellated, which would reflect negatively on the resulting frame rate. When the number of 3D objects visible in the scene becomes excessive, that can create an imbalance in device's performance and reduce its display rate.

Therefore, the final virtual scene would need to be modified to meet our system performance and fidelity targets.

We examined system performance during training segment and the main experiment; the results are shown in Figures 72, 73, and 74. The results suggested that the main scene had 37.1 K triangles, and that system performance during the main experimental session was close to 47 frames per second (FPS).

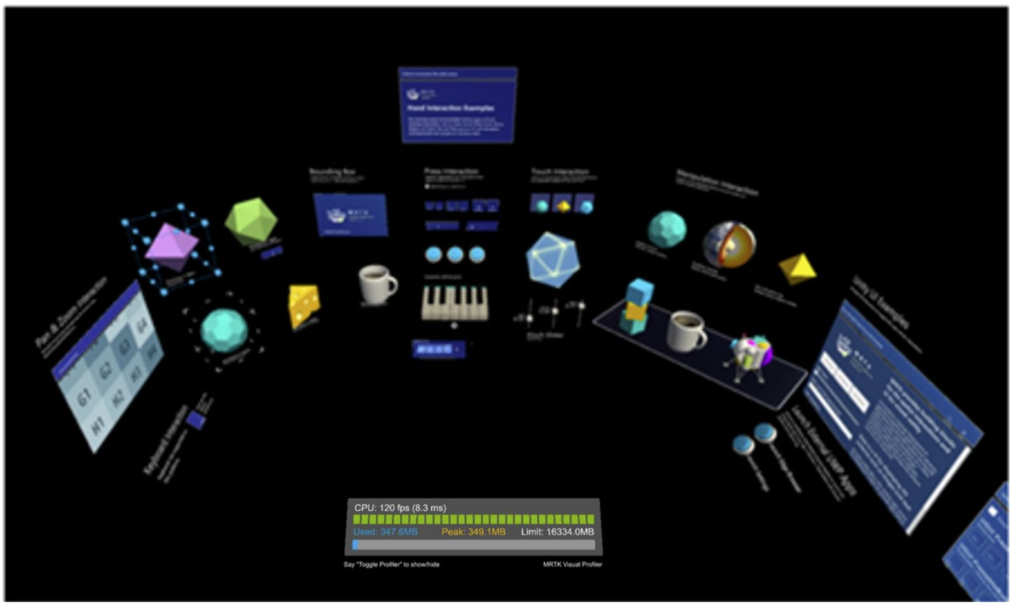


Figure 72. FPS for MRTK training segment

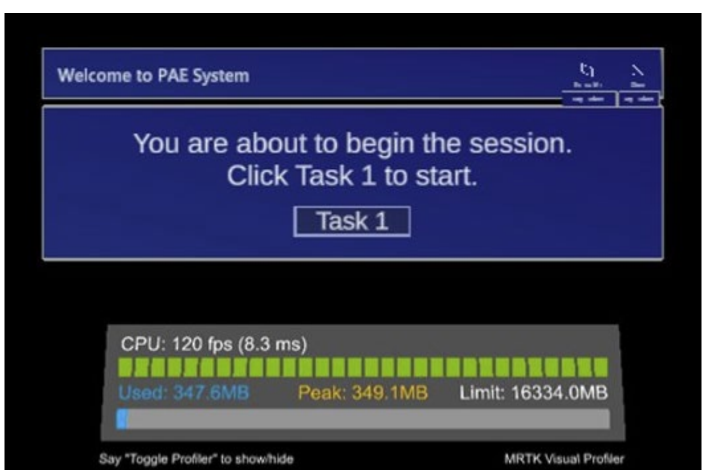


Figure 73. FPS for PAE prototype.

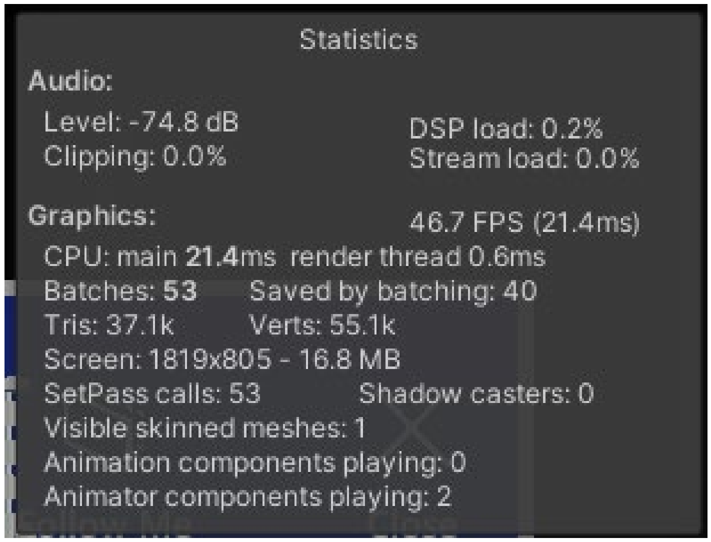


Figure 74. PAE FPS readings.

Being that overall system performance was satisfactory (we did not experience deterioration of the frame rate that would get in the way of user navigation and object interaction), we did not address the issue of further scene optimization; however, we recommend that this particular issue is dealt with in the future.

3. Subjective Data Set

a. Simulator Sickness Questionnaire (SSQ)

The SSQ was given to the participants before the training session, after that session (but before the main session), and after the main session; we transcribed and scored them according to Kennedy et al. scoring criteria [67]. The SSQ consists of 16 questions that evaluate a selected set of participants' symptoms. The symptoms are broken into two major categories: nausea and oculomotor group; each symport is evaluated on a scale from zero to three, where zero corresponds to *None*, one to *Slight*, two corresponds to *Moderate*, and three to *Severe*.

Before starting the training simulations, it was important to determine the baseline values of each symptom (Figure 75). 27% of participants noted slight fatigue before starting the study, followed by the next highest being stomach awareness, sweating, and eye strain at 7%. That could be due to school and life stress on the day of their participation in our study. No participants indicated any symptom at a *Moderate* or *Severe* level.

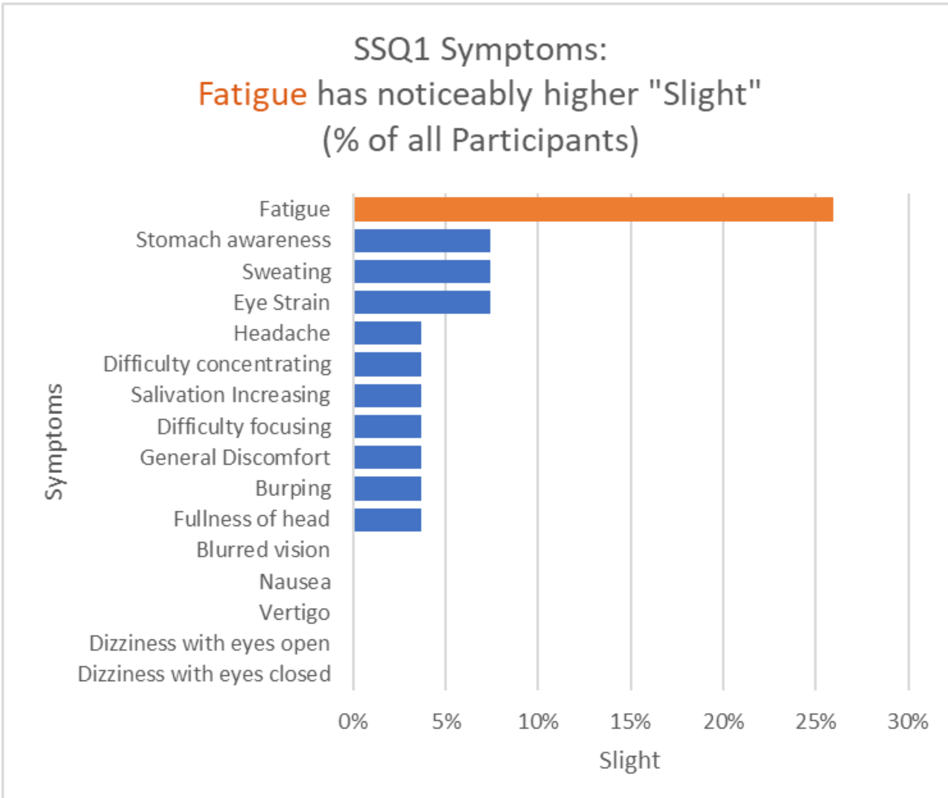


Figure 75. Baseline values for SSQ symptoms (SSQ1).

After the training with two short applications ended, participants completed the pre-task SSQ – SSQ2 to help us evaluate how their symptoms may have been impacted by exposure to the AR environment during the training session (Figure 76). Fatigue was registered by 10% fewer participants, while 10% more participants reported eye strain. Out of the 27% of all participants who noted the eye strain, one indicated it was at a *Moderate* level (the rest of the group indicated it at a *Slight* level). Participants elaborated that the *Slight* and *Moderate* eye strain levels were caused by what they believed to be their unfamiliarity with using the eyewear (HoloLens 2) and the long duration of focusing on 3D objects while simultaneously moving their hands and manipulating the virtual objects. No participants indicated their symptoms at a *Severe* level.

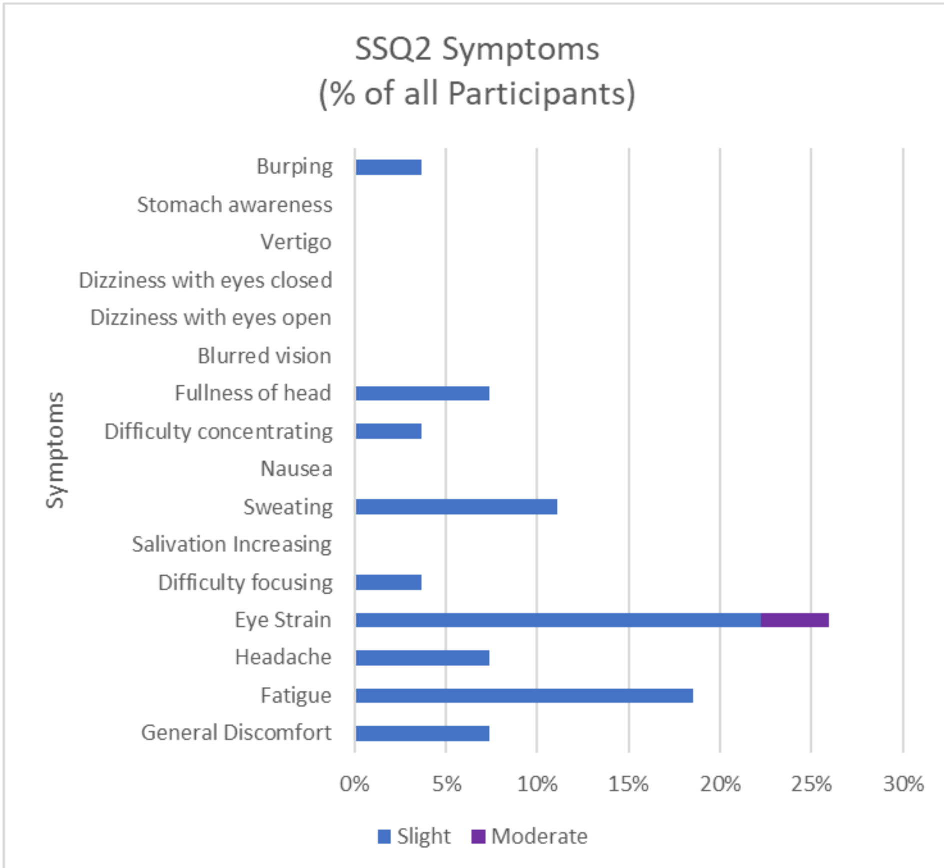


Figure 76. Pre-task SSQ symptoms (SSQ2).

After completing the PAE scenario with three tasks, each participant was instructed to complete the post-task SSQ – SSQ3. The data collected in SSQ3 (Figure 77) report that the eye strain continued to be the lead symptom experienced by 29% of all participants; this was a 2% increase from the values reported in pre-task SSQ – SSQ2 (Figure 76). Fatigue remained constant at 18%. Two new symptoms were reported during the main study – vertigo and stomach awareness experienced by 3% of all participants. The participants who experienced such symptoms noted they were at a *Slight* level. No participants indicated their symptoms at *Moderate* or *Severe* levels.

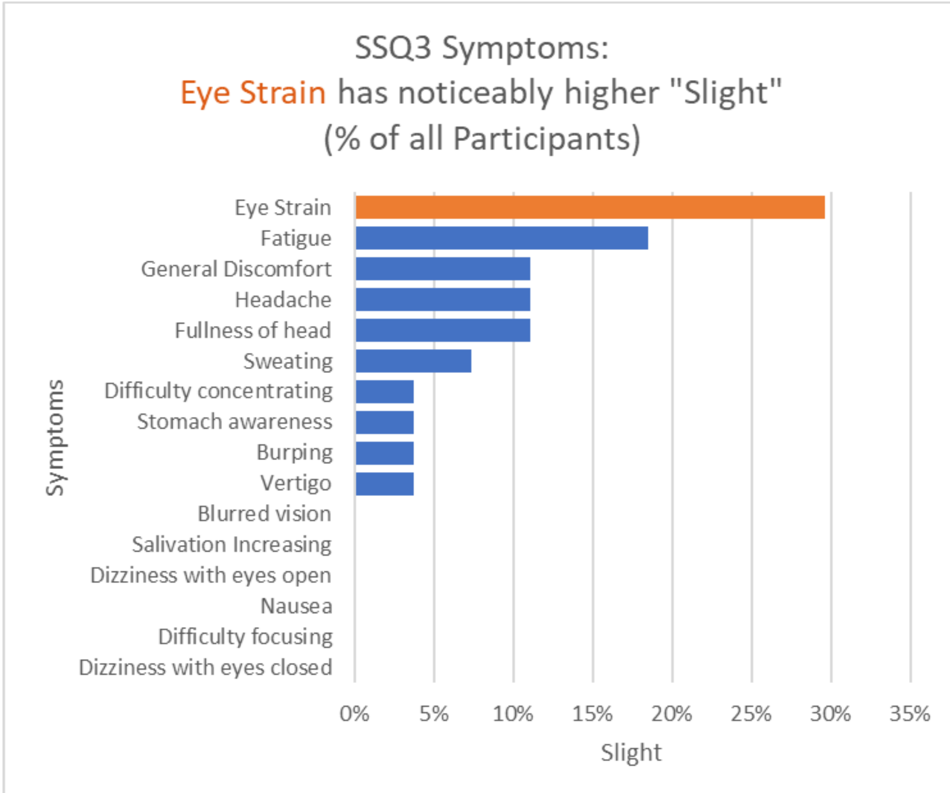


Figure 77. Post-task SSQ symptoms (SSQ3).

Overall, the symptoms did not change for most participants from baseline to post-task SSQs. There was a 7% increase among the participants who experienced *Slight* discomfort from the HoloLens 2 headset, general discomfort, headache, and fullness of the head. This could be attributed to the headset weight added to one's head and the tightness of the device band around the head.

b. System Usability Scale (SUS) Questionnaire

The System Usability Scale (SUS) allows us to examine "the context in which a tool is to be used, and its "appropriateness to that context" or "its fitness for purpose" [67]. The questionnaire also indicates the challenges the users faced during current operations, as discussed in Chapter III.

The frequency of participants' responses for each value is presented in Table 7, and the average responses to each SUS question are presented in Table 8. The maximum average was in question 7 that concerns the ease with which other people could learn to use the system ("I would imagine that most people would learn to use this system very quickly") at 4.21. The minimum average was recorded for question 6 that was related to the system being perceived as having too much inconsistency ("I thought there was too much inconsistency in this system") – it was 1.69.

Table 7. SUS questionnaire: frequency of participants' responses.

	5 = Strongly agree	4 = Agree	3 = Neutral	2 = Disagree	1 = Strongly disagree	Number of participants
1. I think that I would like to use this system frequently	10	10	6	1	0	27 (100%)
2. I found the system unnecessarily complex	0	2	0	16	9	27 (100%)
3. I thought the system was easy to use	6	18	1	2	0	27 (100%)
4. I think that I would need the support of a technical person to be able to use this system	0	5	2	15	5	27 (100%)
5. I found the various functions in this system were well integrated	11	15	0	1	0	27 (100%)
6. I thought there was too much inconsistency in this system	0	1	3	10	13	27 (100%)
7. I would imagine that most people would learn to use this system very quickly	9	15	3	0	0	27 (100%)
8. I found the system very cumbersome to use	0	2	7	11	7	27 (100%)

	5 = Strongly agree	4 = Agree	3 = Neutral	2 = Disagree	1 = Strongly disagree	Number of participants
9. I felt very confident using this system	8	10	6	2	1	27 (100%)
10. I needed to learn a lot of things before I could get going with this system	0	3	0	11	13	27 (100%)

Table 8. SUS questionnaire: Analysis of participant responses. Source: [68].

	Average	Min	Max	StdDev
1. I think that I would like to use this system frequently	4.03	2	5	0.87
2. I found the system unnecessarily complex	1.83	1	4	0.76
3. I thought the system was easy to use	4.03	2	5	0.73
4. I think that I would need the support of a technical person to be able to use this system	2.31	1	4	1.00
5. I found the various functions in this system were well integrated	4.34	2	5	0.67
6. I thought there was too much inconsistency in this system	1.69	1	4	0.81
7. I would imagine that most people would learn to use this system very quickly	4.21	3	5	0.68

	Average	Min	Max	StdDev
8. I found the system very cumbersome to use	2.14	1	4	0.88
9. I felt very confident using this system	3.83	1	5	1.04
10. I needed to learn a lot of things before I could get going with this system	1.76	1	4	0.91
5 = Strongly agree, 4 = Agree, 3 = Neutral , 2 = Disagree, 1 = Strongly disagree				

Table 9. SUS questionnaire: SUS score calculated for each participant.

Participant	SUS score
1	62.50
2	92.50
3	80.00
4	52.50
5	77.50
6	80.00
7	87.50
8	87.50
9	70.00
10	52.50
11	92.50
12	85.00
13	80.00
14	70.00
15	57.50
16	100.00
17	82.50

Participant	SUS score
18	55.00
19	85.00
20	75.00
21	87.50
22	57.50
23	67.50
24	77.50
25	85.00
26	85.00
27	95.00
Average	**77.04**
Min	**52.5**
Max	**100**
StdDev	**13.62**

Tables 7, 8, and 9, and Figures 77 and 78 show the analysis of SUS questionnaires. The average SUS score is 77.04 (Table 9); it suggests that the system is evaluated as being ‘Good’ overall.

The majority of the participants would like to use the PAE frequently (20 participants either agree or strongly agree), they agree about its ease of use (24 participants either agree or strongly agree), they see the system functions well integrated (26 participants either agree or strongly agree), they think that most people would learn it quickly (24 participants either agree or strongly agree) and they felt confident in using the system (18 participants either agree or strongly agree) (Figure 78).

Participants also disagreed that system was complex (25 participants either disagree agree or strongly disagree), that system would need a support of a technical person to use it (20 participants either disagree agree or strongly disagree), that there was inconsistency in the system (23 participants either disagree agree or strongly disagree), that system is cumbersome (28 participants either disagree agree or strongly disagree), and that they would need to learn a lot of things before using it (24 participants either disagree agree or strongly disagree) (Figure 36).

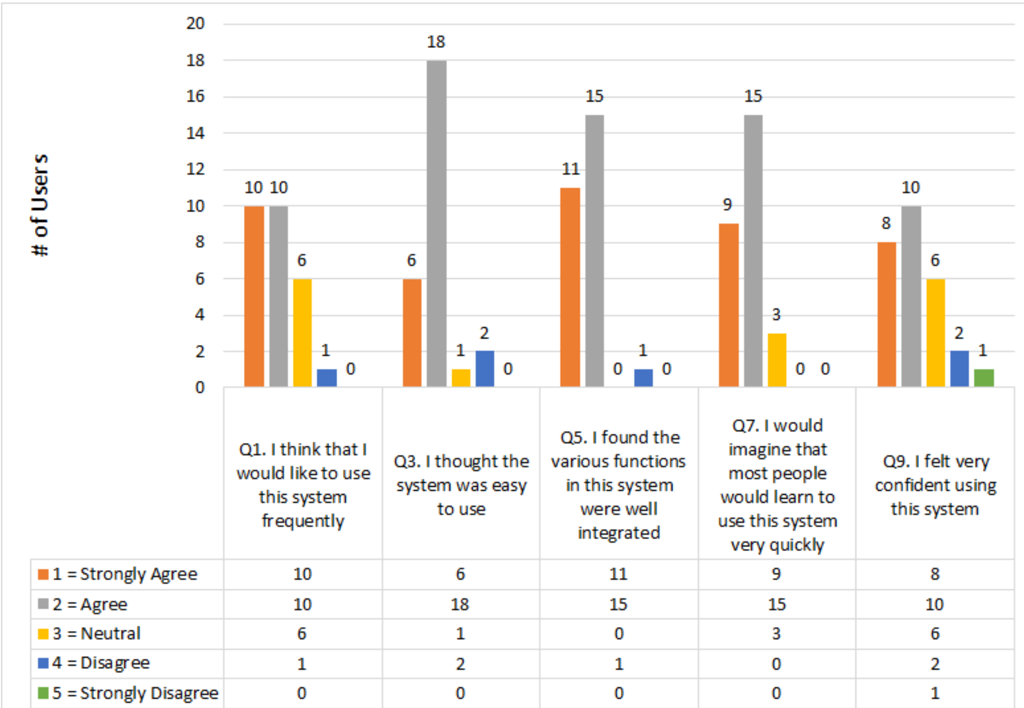


Figure 78. SUS questions referring to the positive characteristics of the system.

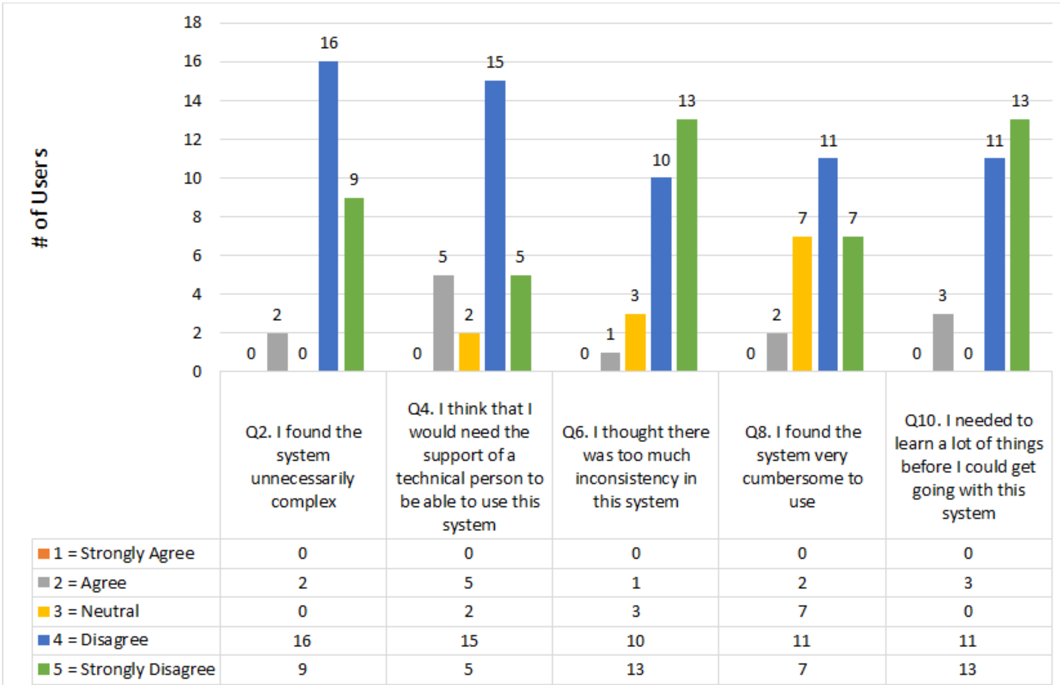


Figure 79. SUS questions referring to the negative characteristics of the system.

There was also one participant who did not feel he or she would use the system frequently; that opinion was based on a personal level of comfort with current forms of information sharing, providing the statement that suggested: “we’ve been taught to use computers and desktops since the fifth grade, why change it.” Nevertheless, the same person shared the opinion of being confident in using the PAE system. Another participant strongly disagreed about feeling confident about using the PAE system, and yet strongly agreed to wanting to use the system frequently.

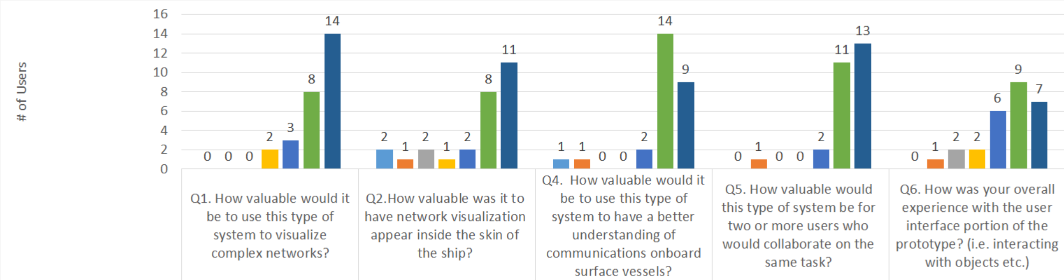
c. Post-task survey

We also collected participants’ responses to 15 post-task questions; the questions allowed participants to reflect on the PAE system, its value, their performance, and any difficulty encountered while using the PAE. Questions 1, 2, 4, 5, and 6 (Figure 80) refer to how valuable the PAE system is, question 3 asked how notional the networks were displayed in the ship (Figure 81), questions 7 through 12 asked about the difficulty of the system (Figure 82), and questions 13 through 15 asks about the performance of the system (Figure 83).

The analysis of data presented in Figure 80 suggests that:

- Question 1: 25 participants (92.59%) found AR visualization of complex networks to be somewhat valuable, valuable, or very valuable.
- Question 2: 21 participants (77.78%) found visualization of the communication networks inside the ship's skin to be somewhat valuable, valuable, or very valuable.
- Question 4: 25 participants (92.59%) found to be somewhat valuable, valuable, or very valuable to use PAE to have a better understanding of communications onboard surface vessels.
- Question 5: 26 participants (96.30%) suggested that it would be somewhat valuable, valuable, or very valuable to use this type of system for group collaboration,
- Question 6: 22 participants (81.48%) found the overall experience with the user interface portion of the prototype to be somewhat easy, easy, or very easy.

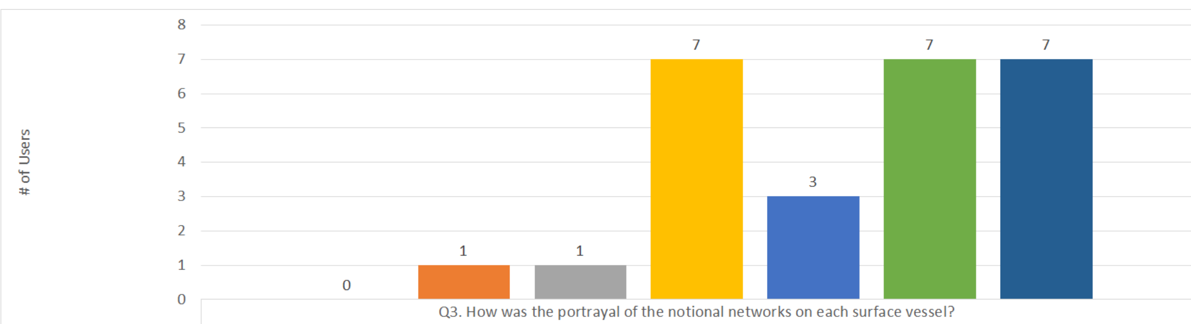
We also observed that, depending on a participant's FOV, they would completely miss to notice the lines of communications visualized within the ship. The lack of experience that some participants had in staff or SME position, requiring an overview of operational statuses, could have altered someone's view on the value of PAE system.



	Q1. How valuable would it be to use this type of system to visualize complex networks?	Q2.How valuable was it to have network visualization appear inside the skin of the ship?	Q4. How valuable would it be to use this type of system to have a better understanding of communications onboard surface vessels?	Q5. How valuable would this type of system be for two or more users who would collaborate on the same task?	Q6. How was your overall experience with the user interface portion of the prototype? (i.e. interacting with objects etc.)
Not Very Valuable	0	2	1	0	0
Not Valuable	0	1	1	1	1
Somewhat Not Valuable	0	2	0	0	2
Neutral	2	1	0	0	2
Somewhat Valuable	3	2	2	2	6
Valuable	8	8	14	11	9
Very	14	11	9	13	7

Figure 80. Responses on the value of the PAE.

Question 3: Even though 62.96% of participants found the portrayal of the lines of communications inside the skin of the ship somewhat to very realistic, 25.93% of participants were neutral, and 7% believed the depiction was somewhat to not realistic (Figure 81). Again, this could have been caused by several factors: the participants' FOV, the position of a ship's menu not facing ships, or participants only reading from the ship's menu and not using the slider to see the changes being simultaneously reflected in visual objects representing the network communications inside the ship.



	Q3. How was the portrayal of the notional networks on each surface vessel?
Not Very Realistic	0
Not Realistic	1
Somewhat Not Realistic	1
Neutral	7
Somewhat Realistic	3
Realistic	7
Very Realistic	7

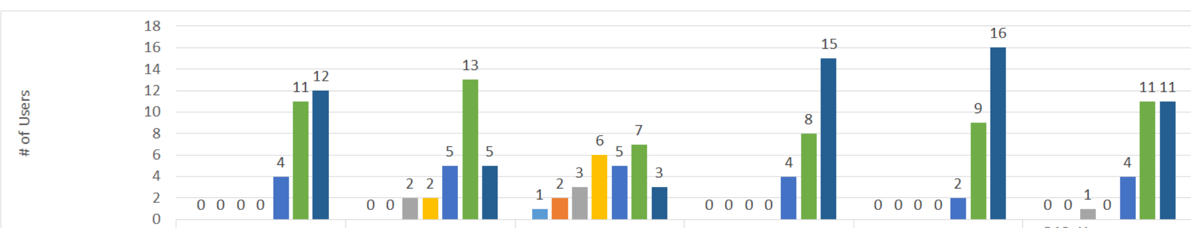
Figure 81. Response for portrayal of lines of communications on each ship.

The next set of questions allowed participants to reflect on different features enabled by the PAE (Figure 82):

- Question 7 (ease of navigation through the scene): All participants (100%) found the navigation in PAE to be slightly easy, moderately easy, or very easy.
- Question 8 (ease of interacting with the menus): 85.18% thought interaction with the menu was slightly easy, moderately easy, or very easy. We observed some participants struggling with the ray cast action, failing to grab the menu with their hands, or not changing their position when trying to interact with the menu. Majority of the participants thought the menu was easy to read and understand, with some requesting the font be a little bigger in the future.
- Question 9 (ease of interacting with the slider): 15 participants (55.56%) found interaction with slider to be slightly easy, moderately easy, or very easy. 6 participants (22%) were neutral, and 5 (18.52%) find the interaction with slider to be somewhat difficult, difficult, or very difficult. The reasons for experiencing the difficulties when interacting with the slider could be cause by difficulties to use ray casting to select the slider. If a participant struggled with ray casting, he or she could typically only read the menu and could not realize the full functionality of the PAE for the duration of the study. Participants also commented that they saw the slider, but they did not manipulate it to understand its functionality; to them it was not obvious that the object represented the slider at the time of task execution. This was probably because the slider object was a flat element in the shape of the light blue rectangle with tiny black arrows inside; those details most likely have passed unnoticed (Figure 83). During the MRTK training, there was an emphasis on the slider objects; however, participants commented that if that specific slider object was in the PAE prototype, it would have been easier to understand. Additionally, participants were reminded after each

task that the slider can only be ray casted; however, only a small number of participants actually manipulated the slider. If the slider was manipulated, some participants could not see the changes happening between the ship and menu due to their narrow FOV. Thus, they did not move their head or physical position to intentionally see the communications networks in the transparent ships. In the future version of the system, we suggest the slider button be changed to the MRTK specific slider object to eliminate any confusion if the slider can be manipulated or not.

- Question 10 (ease of selecting the ships in the scene): All participants (100%) found the selection of ships to be slightly easy, moderately easy, or very easy.
- Question 11 (ease of manipulating the ships in the scene): All participants (100%) found the manipulation with the ships to be slightly easy, moderately easy, or very easy.
- Question 12 (overall experience with the prototype visualization system): 26 participants (96.30%) found the overall experience with the prototype to be slightly easy, moderately easy, or very easy.



	Q7. How easy or difficult was it to navigate through the scene? [	Q8. How easy or difficult was it to interact with the menus?	Q9. How easy or difficult was it to interact with the slider?	Q10. How easy or difficult was it to select the ships in the scene?	Q11. How easy or difficult was it to manipulate the ships in the scene?	Q12. How was your overall experience with the prototype visualization system you used?
Very DIfficult	0	0	1	0	0	0
Moderately Difficult	0	0	2	0	0	0
Somewhat Difficult	0	2	3	0	0	1
Neutral	0	2	6	0	0	0
Slightly Easy	4	5	5	4	2	4
Moderately Easy	11	13	7	8	9	11
Very Easy	12	5	3	15	16	11

Figure 82. Responses on PAE interactive features.

Figure 83. Slider ray-casted from right (right image) to the left (left image) to show the status information that had occurred (and recorded) in the past.

When asked about their own performance in Task 1 (Figure 82, Question 13), 23 participants (85.18%) rated the level of satisfaction with their own performance in Task 1 as slightly satisfied, moderately satisfied, or very satisfied, while two participants (7.41%%) were neutral and two participants (7.41%) were somewhat dissatisfied. We suspect that individuals who were neutral or somewhat dissatisfied felt that way because they were introduced to a new environment, and they did not know if their actions in Task 1 were meeting its objectives.

The answers in questions 14 and 15 (Figure 84) suggest an increase in confidence for all participants; they became more comfortable with the environment, GUI, and the functionality of the PAE. By the end of Task 3, there were no participants who felt dissatisfied with their performance. Only two participants felt neutral, and the majority felt slightly satisfied, moderately satisfied, or very satisfied with their performance.

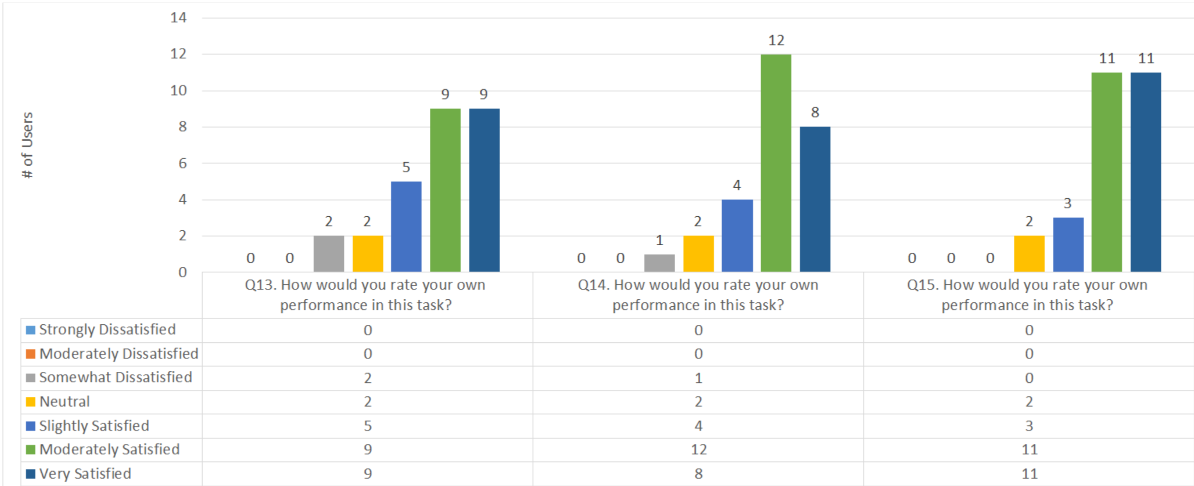


Figure 84. Responses on own performance in Task 1, Task 2, and Task 3 respectively.

d. Behavioral Responses

During the study, we monitored, and video recorded participants' interactions within the PAE to see the PAE from the participants' viewpoint. All participants were able to complete the main study without pausing or terminating the study.

There were some common interactions made by the participants while in the PAE:

1. Participants initially struggled with the ray cast technique but, over time, they were able to successfully use the technique to grab the menus and objects.

2. Use of the slider was limited due to either overlooking the slider, participants having difficulty with ray casting the slider to move left or right or wanting to select the slider with their hands.

3. Participants tended to overlook the slider in the menu and proceeded to only read from it, even if they used the slider and could see the ship and changes within their FOV.

4. All participants could easily read the respective ship's menu and meet the objectives of each task.

5. Participants were hesitant to use the slider on the Communication Status menu or move around the space to view the objects from a different perspective. The proctor noticed that participants were able to grab the objects at their current position, move around the space. The slider could only be ray casted at the beginning of each task, but most participants stood stationary or did limited movement in the physical space around them to manipulate ships.
6. The participants who used the slider did not notice the transparent ships and color changes of the communication networks inside the ships; this was most likely caused by their relative position in space and the narrow FOV in the HoloLens 2.
7. Majority of the participants could see the full functionality for Task 1 and changes occurring between objects and a single ship; however, they did not understand the scope of the full functionality extending to multiple ships in the CSG until the study ended. At the end of the study, they were shown the full functionality of the PAE by the proctors (investigators).
8. Majority of the participants did not see the full system functionality available to them in the scenes presented in Task 2 and Task 3 (situations with multiple ships).

e. Participant feedback

(1) Limitations

There were a few limitations of the HoloLens 2 hardware and software that impacted the study.

- Hardware:

The first limitation was a narrow FOV of the HoloLens 2 headset - participants were limited to a narrow view of the AR environment. Participants demonstrated very limited movement in their immediate physical space. They tended to only focus their view on one position or viewpoint depending on the object they were manipulating or reading from (like menus). The headset reduces a person's peripheral vision that is normally unobstructed without the headset. One participant stated that if they were subjected to the headset more frequently and were trained to look around to see the rest of the space, it would be second nature to account for the lack of peripheral vision. When Microsoft remoting app provides live preview from an active headset and a person's FOV with the headset, the FOV appears to be much wider giving the impression that the FOV is the same for the person who wears the headset, which is not the case. If the headset had a wider FOV, participants could see the entire PAE and notice the changes occurring across the scene while they manipulated the slide object, for example.

The second limitation was the battery life of the HoloLens 2. On average a headset could be used 2 hours before requiring power supply. For the study there was a standby HoloLens 2 available but could have been a serious limitation if one device was inoperable.

- Software:

The first limitation for HoloLens 2 was the anchoring of an application to populate a scene. Prior to the study the training simulations and PAE application are anchored in the controlled room (Figure 42) to easily commence the study and remove room for human errors by participants. Depending on the height of the participant the applications may be too low causing the participant to look down instead of naturally looking up in a normal stance. The application could not always be repositioned for the use to view properly view the objects at his or her eye level. When the scene, or application, would play regardless of the screen being repositioned, the screen would revert back to the low position. This caused us to have to close the application entirely and have participants, with our assistance, place the application at their eye level. For example, HoloLens 2 uses eye tracking to properly populate a scene and if the position of the application screen is below eye level, even if it was adjusted to a participant's eye level, the objects in the PAE will not be correctly positioned.

The second limitation was one of the HoloLens 2 when it stopped communicating with the Microsoft Remoting app. Connecting the device to the Microsoft Remoting app started to time out and lose connectivity on the final day of the usability study.

Unfortunately, there was no workaround to retrieve those files, forcing us to remove them from the collection of data. Attempts to USB-to-C the HoloLens 2 device to retrieve the event log files failed; however, we were able to retrieve the video recordings of participant #24 and #26. This limitation resulted in us losing two system event (excel) files and requiring us to remove the entirety of two participants' data, bringing our participation total from 29 to 27.

(2) Participants' post-study comments

Overall, the participants' experience was highly encouraging; they believed the system would be a major asset for the fleet. Some participants even commented that this should have already been in the fleet years ago. 98% of the participants verbalized their enjoyment while using the PAE and conducting the tasks. They thought the system could eliminate time-late information and provide substantial situation awareness for not only the surface ships but shore commands as well. They felt the system was highly interactive and very intuitive when identifying the causalities and, in return, fully supporting their decision-making. Out of the 27 participants, two participants felt 2D information might be more suitable for communications and networks. One of the two participants stated there may be a benefit; however, that person also felt that wearing a headset for a long period of time could be cumbersome and that the interactions with objects may hinder the requirement to report or understand a casualty in a time-sensitive situation. Another participant thought the presentation of information and the transparent ship required more content to gain the ability to locate the casualty displayed on the ship's menu. Both participants thought the tasks within the PAE should have been more complex and provided more content from an SME's standpoint (i.e., introduce the equipment and sensors and visualize the outages).

All participants were shown the full functionality of the PAE after the post-task survey was completed. They commented that seeing a transparent ship with different types of communications and a menu presenting 3D information provides non-SMEs and SMEs enough information to understand the operational state of a ship or a CSG (Figures 85 and 86). 98% of the participants felt the PAE could assist with understanding an operational picture and support mission planning with its persistent capabilities; they also envisioned possible integration with other systems. Regarding the ship visualization, most participants would like the transparent ship to contain more compartments to see the actual location of an outage or labels on the lines of communications inside the ship's skin. That would allow them to easily identify the type of degradation from a SMEs perspective while still providing an effective overview of ship communications for non-SMEs.

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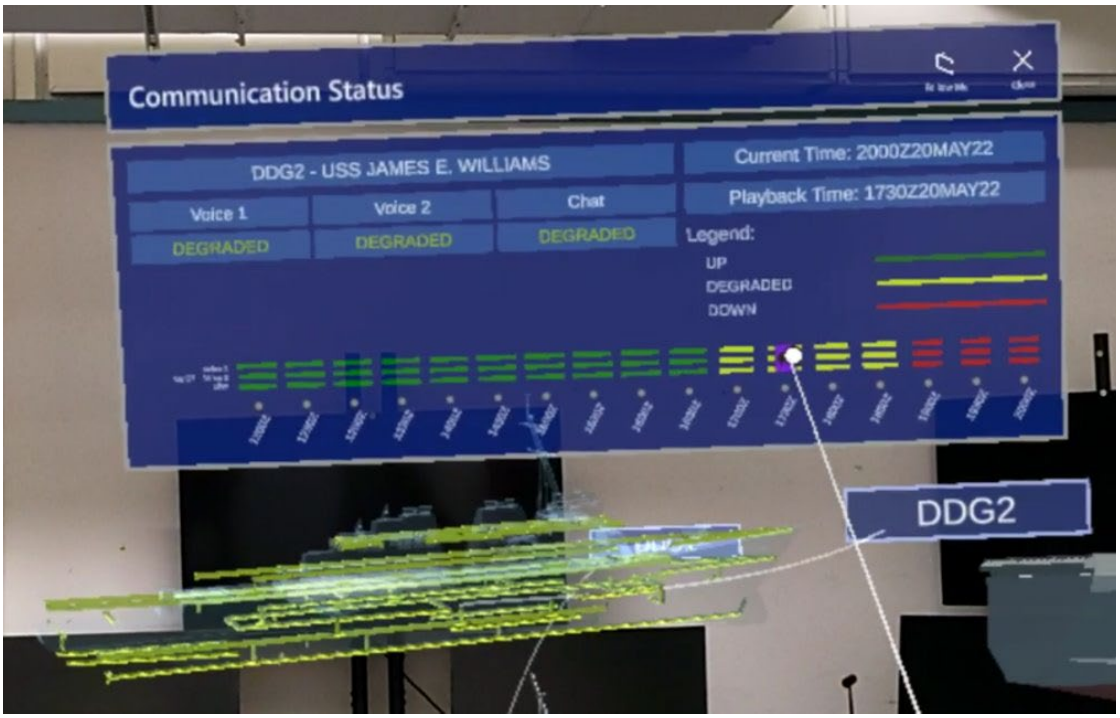

Figure 85. View of a single transparent ship.

Figure 86. View of multiple transparent ships.

G. SUMMARY

This chapter reviewed the elements of usability study: the IRB process, study design, study tasks, a set of objective and subjective data collected in the study, and study procedure. We also provided detailed information about the study participants and analyzed and discussed the data sets collected in the study. Finally, we commented on participants' recommendations for future improvements and expanded application of PAE in the Naval domain.

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VI. CONCLUSION AND FUTURE WORK

A. ADDRESSING THE RESEARCH QUESTIONS

The following research questions were addressed by this study

(1) What is the technological framework that has the potential to provide more efficient support for mission planning?

The Persistent Augmented Environment (PAE) system prototype was found to be the technological framework with great potential in increasing the comprehension of complex networks and supporting decision-making for mission planning. An additional value that became evident was a decrease in the time it took to comprehend the complex networks.

(2) Can the 3D visualization of network communication capabilities and PAE system provide efficient support for elements of mission planning specific to the cyber domain?

Based on the results of the usability study, it was found that the PAE system prototype could be a viable solution that blends SMEs' understanding of the cyber domain and non-SME understanding outside of the cyber domain. The prototype system increased the comprehension and enhanced necessary conditions for decision-making skills that support mission planning and SA within the cyber domain.

(3) Can the PAE system effectively assist mission planning tasks at the tactical level specific to the management of network communications?

It was found that the PAE prototype effectively assisted the planning of mission tasks at the tactical level. Almost all participants provided correct responses to all tasks (only three participants responded incorrectly to Task 2). There was an overall consensus between all participants that the PAE can increase comprehension while decreasing confusion between SMEs and non-SMEs through this more robust, informed C2 decision option.

B. RECOMMENDATIONS TO IMPROVE PAE

The participants in our usability study stated that visualization of communications and networks could positively affect mission planning. Task 2 and task 3 introduced multiple ships and the requirement to identify one or more casualties at a set time. Participants found the visualization of multiple ships from a Composite Warfare Commanders' (CWC) point of view valuable but suggested the PAE system adds Tactical Control (TACON) or Operational Control (OPCON) from a BWC, Commodore, or CO point of view. Using the CVN would be helpful to meet the recommendation of viewing the system from a higher senior officer's POV.

Adding line textures to the timeline objects: We also realized that the only visual characteristic that differentiated different states of readiness for communications was color; the color-blind individuals may miss noticing the difference between those states, thus not being able to execute the tasks correctly. We added the texture to the visualization of the same timelines (Figures 87 and 88) and ensured that even color-blind individuals were fully supported. Only one participant in our study reported having a degree of color blindness; however, that person was still able to differentiate colors used in timelines (green, yellow, and red) and complete the task.

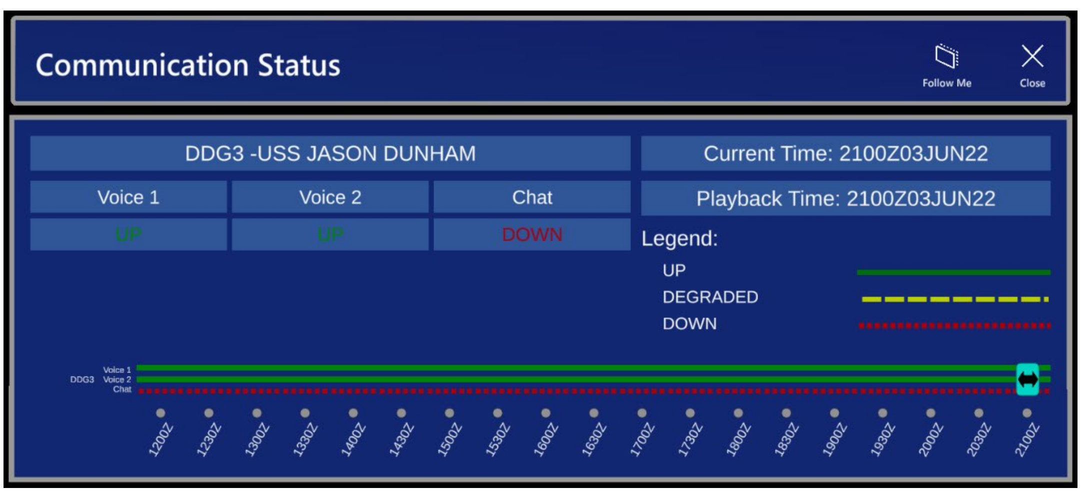

Figure 87. Communication Status menu for one ship with textured timelines.

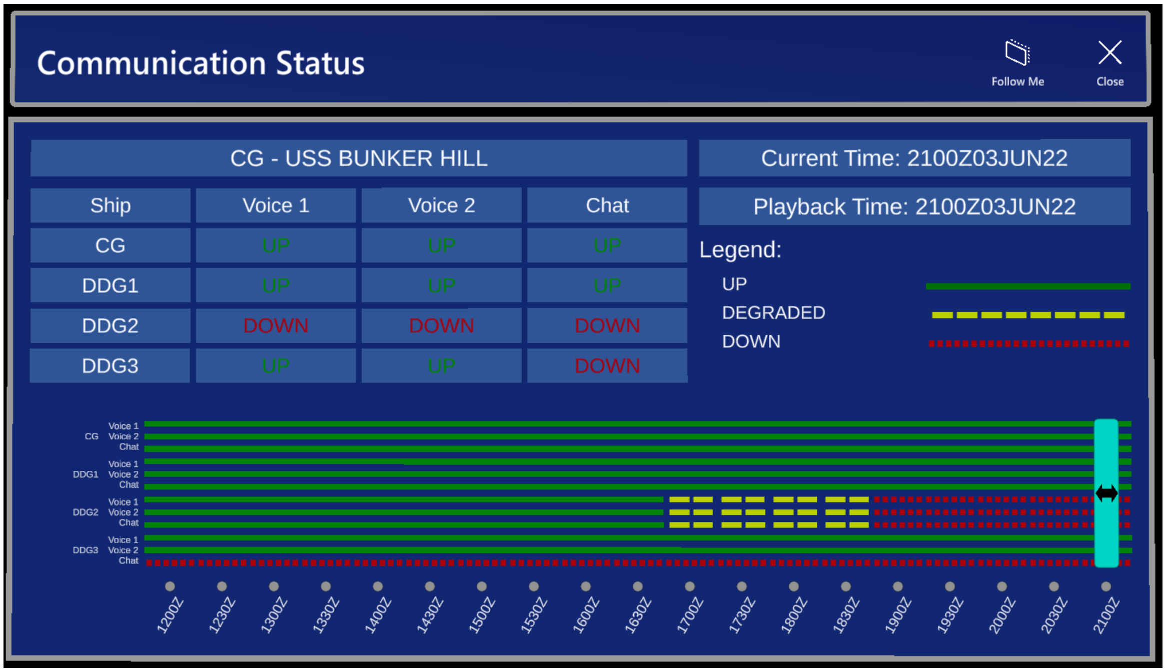

Figure 88. Communication Status menu for multiple ships with textured timelines.

Increase the fidelity of the ship model: Another suggestion for future works is to improve the PAE by adding compartments within the ship to identify the actual location of a casualty. Feedback from multiple participants confirmed that the ability to change their POV from inside the ship's skin would be very valuable – it would allow them to quickly verify the general area or the specific compartment a casualty is located in. Furthermore, this could help them identify what other systems could be affected based on location and degraded system. Most participants noted that the 3D representation of the compartments could be applied to engineering and damage control in a vital way. Specifically, because of the simulation of real-time data, participants said it was helpful to quickly understand the current status of a ship and identify the time a casualty occurred. Adding a menu or tab that shows different casualties and the priority of restoration would be vital from not only an SME's standpoint but also from a decision-maker's point; that person would be able to understand the full scope of a ship and its resources available to complete a specific mission set. Ultimately, adding compartments within the transparent ship would help users to generalize locations on the ship and their potential impact, which further aids in expedited decision-making for casualties. Additionally, by understanding what locations or systems can potentially be affected, the visualization of compartments can help identify redundancies and workarounds between locations faster than asking recommendations from watch standers or relying on one's own mental model or experience of redundancies or workarounds.

PAE supporting collaboration: During the study, the participants verbally reported their findings for Task 1, Task 2, and Task 3, which provided a sense of communicating with others while wearing an AR headset. The current system and supporting usability study were focused on the needs of a single user, and it did not support team collaboration. After the study, some participants noted that the PAE system would be a valuable collaborative tool for training in warfare areas like engineering (for example: help visualize the engineering plant.) That type of capability would be possible to realize; the Microsoft Holographic Remoting App can be utilized in three ways:

1. A co-shared virtual environment in the same location - a user wearing a HoloLens 2 to be in a physical location and another person wearing a HoloLens 2 in the same location.
2. A co-shared virtual environment between remote locations – a user can be in the same location or in a different or remote location.
3. Directly sharing the virtual environment through a desktop - one person could wear a HoloLens 2 while another person can view the PAE from a participant's viewpoint simultaneously on the desktop screen. This is done by connecting to the HoloLens2 IP address, which could be used in a co-shared or remote location.

We believe that further studies of the PAE focused on small team collaboration can benefit the DON in multiple ways. Collaboration can occur between land and sea, as well as between allies, depending on the classification level and need to know. Currently, the PAE is unclassified, but real-time capabilities and data will elevate the classification level of the system. The PAE system can benefit the Fleet for operations of surface ships, and it can be applied to schoolhouses and training commands in preparation for crisis management or proactive training for handling casualties in a non-operational setting. Lastly, collaboration allows users to share information and use it for decision-making. The true benefits of collaboration will have to be researched for future work.

C. DOMAIN CONTRIBUTIONS

The results of the research conducted for this thesis have the potential to bring benefits to multiple domains. In the domain of military decision-making, we examined the value of 3D visualization of communication networks onboard Naval surface vessels using AR display technology. The Navy currently relies on disseminated 2D information throughout a CoC to support the COP and SA of the senior leaders. By using 3D information to visualize the network topologies over the traditional PowerPoint and Daily 8's onboard Naval surface vessels, our study demonstrated that AR visualization resulted in more effective user performance, increased user satisfaction and overall comprehension of the cyber and communications warfare area. While some users experienced difficulties when they started using new interaction techniques supported by the HoloLens 2 (i.e., ray casting operation), most participants stated that, with more practice, they could easily meet task objectives. The participants met all objectives set in the three tasks - they were able to identify degradations and casualties within the CSG. The AR visualization of communication networks onboard a surface vessel allowed participants to understand complex systems very effectively. Consequently, that provided them with a much better SA.

D. FUTURE APPLICATION DOMAINS

Future work in the realm of persistent and AR environments plays a vital role in the Navy's efforts to improve combat readiness throughout the fleet. Our usability study allowed us to collect many recommendations provided by the NPS Naval students; collectively, they have 207 years of experience in the military domain. The experience with the PAE prototype allowed them to consider the use of a similar system in the context of their specific warfare areas, whether it was SWO, IP, CW, or EDO. In this study, we focused on visualizing the cyber warfare area. However, based on the data we collected from the participants, we identified a score of candidate warfare areas and readiness conditions in which the PAE can be used. The main proposed contribution in all those domains is the improvement in training required to understand these complex warfare areas and mission planning responses. These warfare areas include Surface Warfare (SUW), Air Warfare (AW), Antisubmarine Warfare (ASW), Ballistic Missile Defense (BMD), Strike Warfare, and Joint Operations. Readiness conditions include communications, engineering, Damage Control (DC), navigation, maintenance and troubleshooting, and training. Warfare areas that could be supported with PAE in the future:

1. Surface Warfare (SUW) and Antisubmarine Warfare (ASW). In a normal underway steaming scenario of a CSG, an AR display could be used to overlay visual representations of the ships on top of their specific geographical locations to support the SUW and ASW mission sets. Additionally, all internal and external systems within the Naval assets could also be presented as virtual objects. For example, showing the internal connection of the systems (up or down on an ASW capability) within a single semi-transparent ship and external connections between the assets could help share the surface picture for Target Motion Analysis (TMA) against submarines. In other words, we envision using AR to show what each ship has available when tracking a submarine and share real-time data with all ships in the CSG to enhance the crew's understanding of the reasons for the ships' specific maneuvers.

2. Air Warfare (AW). The integration of AR with the aircraft and their navigational tracks can help to validate communications between the air, maritime, and land forces, like through line of sight (LOS) communications. For example, the ability to visualize assets and their corresponding live tracking data can help determine if the communications are out of range based on the geographical area, and it can assist watch standers in locating and tagging specific aircraft. Additionally, visualizing a shared link architecture to validate tracking data between the air and surface forces when working on AW, SUW, or ASW operations, would bring great benefits. That would allow for faster resource management against enemy tracks since it will be easier to visualize validated or intermittent tracking data in real time vice written or voice reports received prior to engagements.

3. Ballistic Missile Defense (BMD) and Strike Warfare. Comprehension of complex information specific to BMD missions could be accelerated by using an AR display to visualize external lines of communications from asset to satellite in 3D. A Commander could quickly visualize BMD circuits, check for redundant communication paths, and quickly manage the deployment of ballistic missiles without fear of loss of redundancy. The same concept of visualizing the interconnection of systems for resource management between different mission sets for BMD can also be applied to strike missions or Surface Action Groups.

4. Joint Forces. The PAE can assist with the visualization of the cross-communication in U.S. military branches and commands that are both complex and unique to specific equipment, networks, and communications. The joint circuits and unique vocabulary used by specific branches can be easily translated into 3D visual objects or even customized based on the users and their needs. For example, the Navy works closely with Marine units for ground transportation; therefore, the PAE system could be used to enhance collaboration between afloat and ground forces. Participants in our user study noted that it was easy to identify loss of communication when using the PAE prototype to assist with SA and planning. Thus, the Marine units on the ground could more easily understand visual information representing the naval communications (and vice versa) available to build and execute operational plans.

E. READINESS CONDITIONS

1. Communications. The PAE was designed to allow users to see a general overview of network status on single or multiple ships by using a panel that displayed that information; additionally, the 3D objects that represented communication networks were shown within a semi-transparent skin of the ship. The consensus among the participants of our user study was in their advice to further detail the network status by physically displaying the compartments, nodes, and switches where a casualty occurred. The participants noted that they would want to see the PAE being used to analyze further casualties at a tactical and operational level. That could be achieved by giving the users the ability to zoom in on the particular location of the casualty, ultimately decreasing time wasted on verbal reports and increasing the amount of time available to make decisions. For example, the location of an actual casualty quickly provides SA to the crew and focuses their efforts on how to allocate resources based on the operational state in a specific AOR. In other words, there is more time to see redundancies and workarounds between the assets, which results in ultimately quicker feedback and faster closure of the decision loop.

2. Enhanced SA for Information Technology (IT) technicians. Displaying a 3D topology of a network that shows different sensors, switches, cryptographic equipment, and other equipment through the persistent system could quickly inform technicians and SMEs and assist them with locating, isolating, and restoring equipment at a faster rate than by traditional means. Also, shore-based commands could be able to see data from systems in real-time to determine if off-ship assistance is required from shore commands. The same visualization could support the SA from multiple telecommunication commands that conduct and monitor information operations.

3. Engineering and Damage Control (DC). Most participants in our study noted that adding the compartments within the transparent ship would provide engineering watch standers with the ability to identify and troubleshoot engineering spaces faster and more accurately. With limited watch standers and the physical limitations of 2D engineering diagrams to visualize all ship spaces, the Engineer Officers of the Watch (EOOW) could potentially visualize and collaborate with watch standers to identify equipment repairs.

4. Enhanced SA for Damage Control Assistant (DCA). As for the damage control operations, the ability to see the ship's compartments and other systems (i.e., fire main lines) in real-time could assist the DCA with damage assessments; that could be more effective than relying on time-late information between multiple repair lockers. It is known that DC plotting is a learned skill; however, by having an improved PAE to include the physical locations of casualties, DCAs can quickly understand what their locker leaders see in real-time and quickly allocate resources to the required spots. Furthermore, that would allow the CO to understand the shared 3D environment and facilitate his/her priorities when deciding what compartments to close off and what spaces to focus on next.

5. Enhanced SA for watch standers. A 3D virtual environment displaying the layout of engineering spaces could enhance understanding of complicated engineering spaces for watch standers; they could learn the skills without needing to go into a specific space. The PAE visualization could be used in place of physical areas when training of the dynamic scenarios cannot happen due to availability, ship schedule, or safety reasons. For example, the PAE system could assist in team training to salvage a ship during internal flooding, collisions at sea, or incoming targets penetrating a ship.

6. Navigation. The PAE system could be used to facilitate training on a unit level or a CSG level; that would exponentially help the current SWO pipeline. There are ship simulators available for training; however, by increasing the availability of ship simulator training through a mobile platform (like the HoloLens 2), AR can exponentially increase navigation training for JO's as Conning Officers; an example of those training scenarios is identification and management of the surface contacts. Furthermore, on a tactical level, training on a CSG level could take advantage of visualizing a top-down view of a battle group. The trainees could plan and practice tactical movements, ultimately providing more avenues for CSG cohesion in training during their pre-deployment time.

7. Maintenance and troubleshooting. The expansion of the PAE functionality to include the ship's compartments and the interconnection of systems and equipment has the potential to assist with maintenance in person or remotely. When a system produces error codes due to a system or equipment fault, it can be daunting for a young Sailor to conduct maintenance for the first time. With AR, the Sailor can easily verify the maintenance card in real-time; the PAE system will always have the most updated version, and it will not be necessary to lug around heavy technical manuals that may be outdated. Since the PAE system is a real-time system with access to historical data sets, it can easily be identified if the maintenance was properly conducted and when and what types of maintenance were done in the past. That can assist with audit checks or provide invaluable insights about the repair of the equipment. Regarding remote assistance from the shore side, SMEs on land could assist a ship away from homeport by using HUD panels to visualize maintenance information and assist with troubleshooting.

8. Training. Current training pipelines for Task Force staff or other training commands use the physical ship systems and configure them to train or assess a specific ship. That is done by staff training teams manipulating the real (or live) equipment. However, participants in our study noted that an AR environment could replace this by having a separate network system to simulate different training objectives, which is ultimately safer and less time consuming for the ship's force. For example, a communication exercise can manipulate a simulated network and conduct the required training objectives without setting a training environment on live equipment. Furthermore, applying simulated networks to a virtual ship could facilitate more effective training since Sailors can visualize the network being trained on and how the intended training objective is supposed to be addressed.

Additionally, in a collaboration sense, the team being evaluated can use PAE in an AAR to see the changes that occurred in the simulated training environment. A collaborative version of PAE could allow the warfighters to see the same operational picture regardless of location and assist them with decision-making, resource management, and troubleshooting.

F. INCORPORATING THE PAE WITH OTHER THESES

The combination of prior work from Huntley [24] using an AR display for DC, Timmerman [8] using an AR display to enable collaboration while visualizing a complex OT network, and work from this thesis using a PAE prototype to visualize networks on their effectiveness on mission planning, the DON can now conduct more research for applying AR technology tactically. These studies demonstrated the ability of the PAE-like system to view assets globally, select the assets to view their operational ship readiness on their respective surface vessels, and zoom into the specific areas onboard ships to determine the casualty locations. Since each study produced positive feedback from participants regarding the value of the AR technology, we believe that incorporating that technology into DON's everyday operations and tasks is justified.

This combination of all three usability studies into a single system could improve decision making, training, collaboration, interconnection of systems, and comprehension of all warfare areas. Based on these studies, it has been proven that AR has the potential to enhance comprehension by visualizing complex systems. Furthermore, a persistent AR system could advantageously provide the DON the capability of receiving real-time data to effectively use this information and rapidly assess battle damage and casualties to swiftly address the situation. In other words, the culmination of a single system using the ideas from all three studies can help resolve major disconnects within communities, provide a better COP to the DON, and potentially include Joint Forces.

G. SUMMARY

In summary, the AR technology and Persistent Augmented Environments, as special cases of AR technology, can be used to enhance decision-making at multiple levels of command; that is done by depicting critical information in an effective way that facilitates intuitive exploration and manipulation of the data set by the users. Future application domains include multiple warfare areas, including cyber, intelligence, engineering, damage control, navigation, weapons systems, combat systems, and maintenance. Even with limited training that was provided to the participants in our study, the PAE was shown to be efficient and effective when participants had to identify information related to degradations or casualties onboard the vessels. Presently, the Navy lacks the body of research in using AR technology to improve the understanding of complex systems or simply receive critical information in a timely and effective manner. The results of our study provide the DON with the necessary insights and motivation to examine the value of AR and PAE-like systems more thoroughly and systematically. The system's overall value also includes its ability to connect teams and team members who are either co-located or connected from remote locations. With the PAE supporting the real-time operation and having access to historical data sets, the new capabilities provided by PAE-like systems to individuals and entire crews could represent much needed critical advantage in their operational readiness.

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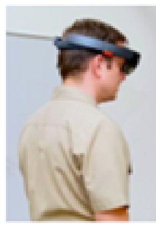
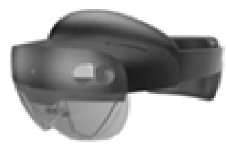
APPENDIX A. RECRUITMENT FLYER

Experience Visualization of Communication Networks on Navy Ships with Augmented Reality (AR)

Help fellow students' thesis research and participate in a Naval Postgraduate School research study entitled "Supporting Mission Planning with a Persistent Augmented Environment (PAE)", which will examine a visualization of the complex communication networks on Naval surface vessels using augmented reality (AR) technology. You will be asked to fill out several questionnaires at the end of your task.

WHAT: You will be asked to make operational decisions based on notional Navy surface vessel network infrastructures.

WHY: Study elements of network visualization in an AR environment

WHO: NPS Navy SWO, CW, and IP students

WHEN: 16-25MAY22 & 31MAY-02JUN22

WHERE: Watkins Hall, Room 212A

LENGTH: About 60 min

SCHEDULE: Email Joanna Cruz and JaMerra Turner

CONTACTS: Student 1: Joanna Cruz
Student 2: JaMerra Turner
Principal investigator: Dr. Amela Sadagic
IRB Chair: Dr. Larry Shattuck

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APPENDIX B. SIMULATOR SICKNESS QUESTIONNAIRE

No______________ Date____________________

SIMULATOR SICKNESS QUESTIONNAIRE

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Instructions : Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. « Fullness of the Head »	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version : March 2013

***Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology, 3*(3), 203-220.

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APPENDIX C. SYSTEM USABILITY SCALE

Subject ID: _______
Date: _______

SUS Questionnaire

**Please reflect and answer the following question based on your experience with the system in this study.*

1. I think that I would like to use this system frequently:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

2. I found the system unnecessarily complex:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

3. I thought the system was easy to use:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

4. I think that I would need the support of a technical person to be able to use this system:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

5. I found the various functions in this system were well integrated:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

6. I thought there was too much inconsistency in this system:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

7. I would imagine that most people would learn to use this system very quickly:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

8. I found the system very cumbersome to use:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

9. I felt very confident using the system:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

10. I needed to learn a lot of things before I could get going with this system:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

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APPENDIX D. DEMOGRAPHICS

Questionnaire

1. Year of Birth: ______
2. Years of Service: ______
3. Current Rank: ______________________________
4. Designator: ____
5. Gender: M / F
6. Are you colorblind?

   YES NO

7. Do you play video games?

   YES NO

   a. If "YES":

      i. How often? (select one that applies)

         a. ___ Less than 2 hrs/wk
         b. ___ 2-4 hrs/wk
         c. ___ 4-8 hrs/wk
         d. ___ More than 8 hrs/wk

      ii. What percentage of each game type do you play? *Ensure that both values add to 100%.*

         single-player ______ % multi-player ______ %

8. Have you used virtual reality or augmented reality head mounted displays before?

   YES NO

   a. If 'YES':

      1. What kind? *(select all that apply)*

         a. ___ HTC Headsets
         b. ___ Oculus Quest
         c. ___ Valve Index
         d. ___ Hololens 1 or 2
         e. ___ Ship or Aircraft Simulators
         f. ___ Other: ____

      2. How many times in the last 5 years? *(select one that applies)*

         a. ___ Only once
         b. ___ Less than 5 times
         c. ___ Between 5 and 10 times
         d. ___ More than 10 times

3. When was the last time you used it? *(select one that applies)*
    a. ___ Within last 30 days
    b. ___ Within last 6 months
    c. ___ Within the last year
    d. ___ More than a year ago

4. Why did you use it? *(select all that applies)*
    a. ___ Personal
    b. ___ Requirement

9. Have you interacted with communication circuits and/or networks on a Surface Vessel before? *(i.e. B2B, Red Phones, satellite phones, internet services etc.)*

    YES NO

    a. If 'YES'
        i. For how long? ________ years.
        ii. Type of interactions?

        ____

10. Have you ever participated in network operations decision-making? *(i.e. TAO, CSO, COMMO, STO, XO, CO)*

    YES NO

    a. If 'YES':
        i. What was/were your role(s)?

        ____

        ii. To what extent were you a part of the decision making for network operations?

        ____

11. How was the network visualized in the past? *(i.e. Tech manuals with topology, 8's, Comms plan, Organization chart, etc.)*
        i. What aspects of that network visualization did you value most? *(what it allowed you to do)*: ____

        ____

        ii. What aspects of that network visualization could be improved or changed? *(what it did not allow you to do):* ____

        ____

APPENDIX E. POST-TASK SURVEY

PAE Network Task

Subject ID: _________
Date: _________

1. How valuable would it be to use this type of system to visualize complex networks?

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

2. How valuable was it to have network visualization appear inside the skin of the ship?

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

3. How was the portrayal of the notional networks on each surface vessel?

1	2	3	4	5	6	7
Not at all realistic	Not realistic	Somewhat not realistic	Neutral	Somewhat realistic	realistic	Very realistic

4. How valuable would it be to use this type of system to have a better understanding of communications onboard surface vessels?

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

5. How valuable would this type of system be for two or more users who would collaborate on the same task?

1	2	3	4	5	6	7
Not very valuable	Not valuable	Somewhat not valuable	Neutral	Somewhat valuable	Valuable	Very valuable

6. **How was your overall experience with the user interface portion of the prototype system?** *(i.e. interacting with objects, finding and interacting with menus etc.)*

1	2	3	4	5	6	7
Very difficult	Moderately difficult	Somewhat difficult	Neutral	Slightly easy	Moderately easy	Very easy

a. If there was any issues, please explain what they were:

1. ______________________________
2. ______________________________
3. ______________________________

PAE Network Task

Subject ID: _________
Date: _________

7. **How easy or difficult was it to navigate through the scene?** *(i.e. move around the three-dimensional models of the ships)*

1	2	3	4	5	6	7
Very difficult	Moderately difficult	Somewhat difficult	Neutral	Somewhat easy	Easy	Very easy

a. If there was any issues, please explain what they were:
1. ______________________________
2. ______________________________
3. ______________________________

8. **How easy or difficult was it to interact with the menus?**

1	2	3	4	5	6	7
Very difficult	Moderately difficult	Somewhat difficult	Neutral	Somewhat easy	Easy	Very easy

a. If there was any issues, please explain what they were:
1. ______________________________
2. ______________________________
3. ______________________________

9. **How easy or difficult was it to interact with the slider?**

1	2	3	4	5	6	7
Very difficult	Moderately difficult	Somewhat difficult	Neutral	Somewhat easy	Easy	Very easy

a. If there was any issues, please explain what they were:
1. ______________________________
2. ______________________________
3. ______________________________

10. **How easy or difficult was it to select the ships in the scene?**

1	2	3	4	5	6	7
Very difficult	Moderately difficult	Somewhat difficult	Neutral	Somewhat easy	Easy	Very easy

a. If there was any issues, please explain what they were:
1. ______________________________
2. ______________________________
3. ______________________________

PAE Network Task

Subject ID: _________
Date: _________

11. How easy or difficult was it to manipulate the ships in the scene?

1	2	3	4	5	6	7
Very difficult	Moderately difficult	Somewhat difficult	Neutral	Somewhat easy	Easy	Very easy

a. If there was any issues, please explain what they were:
   1. ______________________________
   2. ______________________________
   3. ______________________________

12. How was your overall experience with the prototype visualization system you used?

1	2	3	4	5	6	7
Very difficult	Moderately difficult	Somewhat difficult	Neutral	Slightly easy	Moderately easy	Very easy

a. If there was any issues, please explain what they were:
   1. ______________________________
   2. ______________________________
   3. ______________________________

13. For Task 1 *(Single Ship)*

a. How would you rate your own performance in this task?

1	2	3	4	5	6	7
Strongly dissatisfied	Moderately dissatisfied	Somewhat dissatisfied	Neutral	Slightly satisfied	Moderately satisfied	Very satisfied

b. What did you like about the task?
   1. ______________________________
   2. ______________________________
   3. ______________________________

c. What did you dislike about the task?
   1. ______________________________
   2. ______________________________
   3. ______________________________

d. What improvements would you want to see regarding the task and visualization that supported it?
   1. ______________________________
   2. ______________________________
   3. ______________________________

14. For Task 2 *(Multi Ship)*

a. How would you rate your own performance in this task?

1	2	3	4	5	6	7
Strongly dissatisfied	Moderately dissatisfied	Somewhat dissatisfied	Neutral	Slightly satisfied	Moderately satisfied	Very satisfied

b. What did you like about the task?
   1. ______________________________
   2. ______________________________
   3. ______________________________
c. What did you dislike about the task?
   1. ______________________________
   2. ______________________________
   3. ______________________________
d. What improvements would you want to see regarding the task and visualization that supported it?
   1. ______________________________
   2. ______________________________
   3. ______________________________

15. For Task 3 *(Multi Ship with TASKORD)*

a. How would you rate your own performance in this task?

1	2	3	4	5	6	7
Strongly dissatisfied	Moderately dissatisfied	Somewhat dissatisfied	Neutral	Slightly satisfied	Moderately satisfied	Very satisfied

b. What did you like about the task?
   1. ______________________________
   2. ______________________________
   3. ______________________________
c. What did you dislike about the task?
   1. ______________________________
   2. ______________________________
   3. ______________________________
d. What improvements would you want to see regarding the task and visualization that supported it?
   1. ______________________________
   2. ______________________________
   3. ______________________________

16. **Additional Comments/Remarks:**

____
____
____
____
____

SUPPLEMENTAL

There are three files contained within the .zip file.

(1) "Short Video Demonstration of PAE Overview_1 of 3"

Description: This four minute and fourteen second video demonstrates a short PAE overview.

(2) "Long Video Demonstration of PAE Functionality_2 of 3"

Description: This eight minute and four second video demonstrates the PAE functionality through a step-by-step walkthrough of the three tasks found in the usability study.

(3) "PowerPoint Brief Thesis Overview_3 of 3"

Description: This brief is an overview of our thesis in a concise PowerPoint format.

For those interested in obtaining the supplemental information, contact the NPS library.

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