2022-06

# EXPLORING THE ABILITY TO EMPLOY VIRTUAL 3D ENTITIES OUTDOORS AT RANGES BEYOND 20 METERS

Morris, John R.

Monterey, CA; Naval Postgraduate School

https://hdl.handle.net/10945/70707

# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**EXPLORING THE ABILITY TO EMPLOY VIRTUAL 3D ENTITIES OUTDOORS AT RANGES BEYOND 20 METERS**

by

John R. Morris

June 2022

Thesis Advisor: Quinn Kennedy
Co-Advisor: Perry L. McDowell
Second Reader: Larry C. Greunke

**Research for this thesis was performed at the MOVES Institute.**

THIS PAGE INTENTIONALLY LEFT BLANK

| REPORT DOCUMENTATION PAGE | *Form Approved OMB No. 0704-0188* |
|---|---|



| **1. AGENCY USE ONLY** ***(Leave blank)*** | **2. REPORT DATE** June 2022 | **3. REPORT TYPE AND DATES COVERED** Master's thesis |
|---|---|---|

| | |
|---|---|
| **4. TITLE AND SUBTITLE** EXPLORING THE ABILITY TO EMPLOY VIRTUAL 3D ENTITIES OUTDOORS AT RANGES BEYOND 20 METERS | **5. FUNDING NUMBERS** |
| **6. AUTHOR(S)** John R. Morris | |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** Naval Postgraduate School Monterey, CA 93943-5000 | **8. PERFORMING ORGANIZATION REPORT NUMBER** |
| **9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)** N/A | **10. SPONSORING / MONITORING AGENCY REPORT NUMBER** |

**11. SUPPLEMENTARY NOTES** The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

| **12a. DISTRIBUTION / AVAILABILITY STATEMENT** Approved for public release. Distribution is unlimited. | **12b. DISTRIBUTION CODE** A |
|---|---|

**13. ABSTRACT (maximum 200 words)**

The Army is procuring the Integrated Visual Augmentation System (IVAS) system to enable enhanced night vision, planning, and training capability. One known limitation of the IVAS system is the limited ability to portray virtual entities at far ranges in the outdoors due to light wash out, accurate positioning, and dynamic occlusion. The primary goal of this research was to evaluate fixed three-dimensional (3D) visualizations to support outdoor training for fire teams through squads, requiring target visualizations for 3D non-player characters or vehicles at ranges up to 300 m. Tools employed to achieve outdoor visualizations included GPS locational data with virtual entity placement, and sensors to adjust device light levels. This study was conducted with 20 military test subjects in three scenarios at the Naval Postgraduate School using a HoloLens II. Outdoor location considerations included shadows, background clutter, cars blocking the field of view, and the sun's positioning. Users provided feedback on identifying the type of object, and the difficulty in finding the object. The results indicate GPS only aided in identification for objects up to 100 m. Animation had a statistically insignificant effect on identification of objects. Employment of software to adjust the light levels of the virtual objects aided in identification of objects at 200 m. This research develops a clearer understanding of requirements to enable the employment of mixed reality in outdoor training.

| | |
|---|---|
| **14. SUBJECT TERMS** mixed reality, augmented reality, outdoors, training, integrated visual augmentation system, IVAS, Army, Marines, three-dimensional, 3D | **15. NUMBER OF PAGES** 77 |
| | **16. PRICE CODE** |

| **17. SECURITY CLASSIFICATION OF REPORT** | **18. SECURITY CLASSIFICATION OF THIS PAGE** | **19. SECURITY CLASSIFICATION OF ABSTRACT** | **20. LIMITATION OF ABSTRACT** |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | UU |

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

THIS PAGE INTENTIONALLY LEFT BLANK

# EXPLORING THE ABILITY TO EMPLOY VIRTUAL 3D ENTITIES OUTDOORS AT RANGES BEYOND 20 METERS

John R. Morris
Lieutenant Colonel, United States Army
BS, Texas Agricultural and Mechanical University, 2005
MMAS, United States Army Command and General Staff College, 2016

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN MODELING, VIRTUAL ENVIRONMENTS, AND SIMULATION**

from the

**NAVAL POSTGRADUATE SCHOOL**
**June 2022**

Approved by: Quinn Kennedy
Advisor

Perry L. McDowell
Co-Advisor

Larry C. Greunke
Second Reader

Gurminder Singh
Chair, Department of Computer Science

THIS PAGE INTENTIONALLY LEFT BLANK

# ABSTRACT

The Army is procuring the Integrated Visual Augmentation System (IVAS) system to enable enhanced night vision, planning, and training capability. One known limitation of the IVAS system is the limited ability to portray virtual entities at far ranges in the outdoors due to light wash out, accurate positioning, and dynamic occlusion. The primary goal of this research was to evaluate fixed three-dimensional visualizations to support outdoor training for fire teams through squads, requiring target visualizations for 3D non-player characters or vehicles at ranges up to 300 m. Tools employed to achieve outdoor visualizations included GPS locational data with virtual entity placement, and sensors to adjust device light levels. This study was conducted with 20 military test subjects in three scenarios at the Naval Postgraduate School using a HoloLens II. Outdoor location considerations included shadows, background clutter, cars blocking the field of view, and the sun's positioning. Users provided feedback on identifying the type of object, and the difficulty in finding the object. The results indicate GPS only aided in identification for objects up to 100 m. Animation had a statistically insignificant effect on identification of objects. Employment of software to adjust the light levels of the virtual objects aided in identification of objects at 200 m. This research develops a clearer understanding of requirements to enable the employment of mixed reality in outdoor training.

THIS PAGE INTENTIONALLY LEFT BLANK

# TABLE OF CONTENTS

I. INTRODUCTION....1
- A. MOTIVATION....1
- B. BACKGROUND....2
- C. MIXED REALITY FOR GROUND FORCES....2
  - 1. Recent History....2
  - 2. Ongoing Research....3
  - 3. Challenges....3
- D. VISUAL PERSPECTIVE IN MIXED REALITY....4
  - 1. Background....4
  - 2. Human Depth Assessment....4
  - 3. Depth Cues Deep Dive....5
  - 4. Technical Tools and Solutions....6
- E. WORLD LOCK/GEO-LOCATIONAL ANCHORING....7
  - 1. Background....7
  - 2. Spatial Mapping Methods....7
  - 3. Typical Spatial Mapping Steps....7
  - 4. Spatial Mapping Outdoors....8
  - 5. Current Use Case: Tourism....8
  - 6. IVAS Spatial Mapping Approach....9
  - 7. IVAS Spatial Mapping Challenges and Potential Solutions....9
- F. MIXED REALITY TRACKING....10
  - 1. Background....10
  - 2. GPS....10
  - 3. Outside-In....11
  - 4. Simultaneous Localization and Mapping (SLAM)....11
  - 5. Remedies....11
- G. HEALTH AND SAFETY CONSIDERATIONS....14
- H. RESEARCH QUESTIONS....15

II. PILOT TESTING....17
- A. PHASE 1: PREPARATION....17
- B. PHASE 2: PILOT TESTING....17
  - 1. Phase 2a, Familiarization....18
  - 2. Phase 2b, Software and Positional Testing....19
  - 3. Phase 2c, Formal Pilot Testing....19
- C. SUMMARY....20

III. OBSERVATIONAL STUDY METHODOLOGY .......... 21
A. STUDY PARTICIPANTS .......... 21
B. IDENTIFICATION TASKS AND SCENARIOS .......... 22
C. SURVEYS .......... 26
1. Demographic Survey .......... 26
2. Feedback or Post-Test Survey .......... 26
D. EQUIPMENT .......... 26
E. PROCEDURES .......... 27

IV. RESULTS .......... 29
A. DATA PREPARATION .......... 29
B. STATISTICAL ANALYSIS .......... 29
C. PRELIMINARY ANALYSIS .......... 30
1. Visibility Ratings by Scenario and Distance .......... 30
2. Visibility Results by Objects .......... 32
D. RESEARCH QUESTION 1 .......... 33
E. RESEARCH QUESTION 2 .......... 38
F. EXPLORATORY QUESTION: TO WHAT EXTENT CAN ADJUSTED LIGHT LEVELS OF 3D ENTITIES SUPPORT IDENTIFICATION AT RANGES OF 20–300 M? .......... 40
1. Software Performance at 50 m .......... 40
2. Software Performance at 100 m .......... 41
3. Software Performance at 200 m .......... 43
G. DEMOGRAPHIC AND POST-TASK SURVEY .......... 44

V. CONCLUSIONS .......... 47
A. SUMMARY OF RESULTS .......... 48
1. GPS Contribution .......... 48
2. Animation .......... 49
3. Software Lighting Adjustment Capability .......... 50
B. LIMITATIONS .......... 51
C. FUTURE WORK .......... 52
D. CONCLUSION .......... 54

APPENDIX. SURVEYS .......... 55
A. DEMOGRAPHIC SURVEY .......... 55
B. POST-TASK SURVEY .......... 56

LIST OF REFERENCES .......... 57

INITIAL DISTRIBUTION LIST .......... 59

# LIST OF FIGURES

Figure 1. NPS campus map with the three scenario locations shown by number.....23
Figure 2. Scenario 1, Hermann Hall, facing north ....................................................24
Figure 3. Hermann Hall, facing southeast, Scenario 2.............................................25
Figure 4. Hermann Hall, facing north, Scenario 3 ...................................................26
Figure 5. Likert ratings by object and range ............................................................30
Figure 6. Frequencies for Likert ratings 1– 5 by distance........................................31
Figure 7. User outcomes for VEs at 50 m ................................................................31
Figure 8. Likert ratings frequencies for visibility of VEs at 100 m ..........................32
Figure 9. Likert ratings frequencies for visibility of VEs at 200 m ..........................33
Figure 10. Contingency analysis of rating by scenario and distance, 50 m ................35
Figure 11. Contingency analysis of rating by scenario and distance, 50 m ................36
Figure 12. Contingency analysis of rating by scenario and distance, 200 m ..............37
Figure 13. Chi- square analysis of animation by distance, 50 m................................39
Figure 14. Grouped mean analysis, animated vs. non-animated................................40
Figure 15. Software mosaic plot, contingency table, Chi- square test, 50 m .............41
Figure 16. Software mosaic plot, contingency table, Chi- square test 100 m ............42
Figure 17. Software mosaic, contingency table, Chi- square test, 200 m .................43
Figure 18. Subject rating by previous enemy identification training ..........................45

THIS PAGE INTENTIONALLY LEFT BLANK

# LIST OF TABLES

Table 1. Demographic descriptors ....................22

Table 2. Post-task survey, MR potential in demanding training environment ........46

Table 3. Post-task survey, complicating environmental factors ....................46

THIS PAGE INTENTIONALLY LEFT BLANK

# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| 3D | three-dimensional |
| ANS | automatic nervous system |
| AHRS | Attitude Heading Reference System |
| AR | augmented reality |
| CCLTF | Close Combat Lethality Task Force |
| CI | confidence interval |
| D | disorientation |
| DSTS | Dismounted Soldier Training System |
| FOV | field of view |
| GPS | Global Positioning System |
| HUD | heads up display |
| JRTC | Joint Readiness Training Center |
| IVAS | Integrated Visual Augmentation System |
| MR | mixed reality |
| N | nausea oculomotor |
| NPS | Naval Postgraduate School |
| NPC | non-player character |
| O | oculomotor |
| OCT | Observer, Controller, Trainer |
| SiVT | Squad immersive Virtual Trainer |
| SLAM | Simultaneous Localization and Mapping |

THIS PAGE INTENTIONALLY LEFT BLANK

# ACKNOWLEDGMENTS

Thank you to my wife, Kacie, and our two children, Finn and Vivienne. I was able to complete my studies at the Naval Postgraduate School because of your sacrifice and understanding. Kacie, you have sacrificed your career, health, and personal time to allow me to complete my military career. You have also spent months alone with our children ensuring they have all of the love and care that can possibly be provided. I am also thankful to my parents for ensuring I was provided with the educational background, love, and values to complete the rigorous NPS curriculum.

To Dr. Quinn Kennedy, thank you for the expert advice and resources that saved me countless hours, and enabled me to complete this thesis. Thank you, Mr. Perry McDowell and Mr. Clay Greunke, for the technical guidance and technological resources that enabled me to complete this research.

Virtual Reality Rehab’s research and software was critical to enabling my research. I specifically want to thank Dutch, Mr. Kevin Hernandez, and Mr. Mike Maulbeck for their expertise, which enabled the customization of the software to support my research.

I would also like to thank COL Carlos Kavetsky, Mr. Neil Pinto, Mr. Blake Aycock, Mr. Jimmy King, Mr. William Jones, and Mr. Christian Fitzpatrick for their support in ensuring the IVAS HUD was available. This technology and expertise provided by the personnel mentioned enabled my greater understanding of the abilities of mixed reality and supporting technologies.

THIS PAGE INTENTIONALLY LEFT BLANK

# I. INTRODUCTION

## A. MOTIVATION

During my first 10 years of service as a Field Artillery officer in light infantry brigades, we were often challenged to employ realistic, mobile targets for training engagements. This challenge also extended to tactical rehearsals without troops where leaders sought to visualize the training event during terrain walks at the actual training site. In the combat environment, it is even more difficult to maintain live fire skills as it is challenging to engage most targets on an installation smaller than a football field.

Upon completion of command, I served as an Observer, Coach, Trainer (OCT) at the Army's Joint Readiness Training Center (JRTC) Live Fire Task Force. As the officer responsible for planning most engagements with live weapon systems for any weapon larger than a grenade, I struggled to replicate realistic engagements. Fixed targets such as tanks often disintegrated beyond recognition after approximately 100 direct artillery strikes, and engaging moving targets was impractical. Both types of targets are challenging to replace due to cost and safety concerns. This research is designed to mature the military's ability to leverage mixed reality (MR) outdoors in order to provide realistic training. Ultimately, this thesis supports achievement of the Department of Defense Close Combat Lethality Task Force goal of "25 'battles' before the first battle begins" (Schogol, 2018, as cited in Roper, 2018, p. 5). The target audience this research supports are soldiers in close combat forces. As the technology matures, it will support all Army combat arms. Furthermore, it enables key support warfighters such as medics and combat engineers. The research serves as a basis that improves upon existing training targets, whose complexity is limited to pop-up or fixed track moving targets engaged from fixed positions. Once the Army has the means to provide virtual 3D outdoor and mobile targets, training realism will dramatically improve as gaming and virtual reality research can be taken outdoors. Improved realism reduces the shock of the first contact during combat, meaning warfighters are able to anticipate enemy actions without experiencing combat.

## B. BACKGROUND

The following background information discusses key challenges concerned with employing MR outdoors. This chapter begins with a discussion on the background and requirements for MR support of ground forces. It then transitions to topics including virtual perspective in MR, MR virtual tracking, world-lock geo-locational anchoring, and health and safety, followed by the research questions. The intent of this chapter is to explain key challenges, research, and approaches to remedy them.

## C. MIXED REALITY FOR GROUND FORCES

### 1. Recent History

The United States (U.S.) military, specifically the Army and Marine Corps, has pursued many routes to add features that occur in real operational settings that cannot be safely replicated during live training. A relatively early effort sought to incorporate virtual reality into dismounted infantry training with the development of the Dismounted Soldier Training System (DSTS) (Bymer, 2012). In the early 2010s, infantry units were provided a few DSTS units, but they were largely rejected by the users due to their limited mobility, which confined the system to a small indoor environment. However, it is worth noting that some infantry units accepted the system and used it. Furthermore, analysis of DSTS user feedback suggested that augmented/mixed reality would assist in solving capability gaps presented by the system (Reitz & Seavey, 2016). In the mid-2010s, the Navy and Army conducted market research through a phase-3 Small Business Innovative Research contract with Magic Leap Horizons, which validated the potential for mixed reality headsets to support training. In 2018, Microsoft bid and won a two-year research and prototyping contract valued at approximately $480 million to develop the Integrated Vistal Augmentation System (IVAS), which is based on the HoloLens mixed reality Heads Up Display (HUD) (Haselton, 2019). The Army approved the IVAS contract as a way to train Soldiers to achieve combat overmatch. The Close Combat Lethality Task Force (CCLTF) study defined close combat overmatch as "the ability of a squad-sized unit to impose its will on a similar sized opponent under all conditions and operational environments" (Mattis, 2018, as cited by Roper, 2018, p. 2).

### 2. Ongoing Research

Currently, both live and virtual training lack the ability to employ virtual three-dimensional (3D) targets outdoors at ranges beyond 20 m (Aycock, 2021). The Army has sought this capability to increase realism during training and rehearsal events. This increased realism was initially explored using virtual reality in a fixed training area. Recently, it was explored under the IVAS prototyping effort, which is based on the Microsoft HoloLens mixed reality hardware. The prototyping effort developed new hardware and software based on the HoloLens for night vision, thermal vision, navigation, rehearsal, and training. While the IVAS prototyping effort successfully executed a proof of concept for outdoor employment, as of fall 2020 it lacked the ability to support training engagements at ranges beyond 30 m and dynamic occlusion. Due to the delay in hardware development and limited follow-on time within the prototyping contract, the outdoor capability was not matured.

Additionally, the Army still needs to enhance fidelity of the models to ensure believable movement of objects at the furthest perceivable ranges. Increased fidelity allows users to train on both location and orientation to target, plus detailed target identification. For example, this capability gives users the ability to identify the type of vehicle or confirm a target as an enemy combatant.

### 3. Challenges

The challenges identified from previous prototyping research and the IVAS program are as follows. Practitioners and subject matter experts have identified similar challenges:

- The IVAS system has difficulty handling the occlusion of 3D VEs by real world objects which frequently move, such as tall grass.
- HUDs do not consistently present objects in the same location for all users when there are holes in the spatial map. This happens when one user places a virtual object on a flat table, and another user sees the object “floating” above the table.

- Non-player characters NPCs are unable to conduct advanced AI driven navigation. Current behaviors are limited to a one or two step prescribed navigation sequence, making behaviors predictable.
- Significant changes in light levels within the user's field of view (FOV) can significantly degrade the quality of VEs (VEs) at distances beyond 30 m.

## D. VISUAL PERSPECTIVE IN MIXED REALITY

### 1. Background

It is critical in virtual environments for users to identify 3D VEs, especially in MR environments. This is especially challenging outdoors when VEs are placed in the FOV at ranges beyond those typically found in a home or office. These ranges can be referred to as distant ranges in the context of MR. Distant ranges are defined as those beyond 30 m from the observer (Cutting & Vishton, 1995). Our research focuses on distant ranges up to 200 m. To identify VEs up to 200 m, we must somehow determine the distance of known objects in the scene.

In order to properly identify an object at a distant range, users must be able to identify the 3D object. Therefore, the perspective at varying ranges must be correct. Even if a visual display cannot properly generate the perspective and subsequent visualization, other techniques may exist to support identification of a virtual object. The following sections discuss human depth assessment, depth cues, and technical tools to provide familiarize the reader with human depth perception in the context of MR employment.

### 2. Human Depth Assessment

Humans assess depth through both proprioceptive and visual cues to provide depth and distance for near ranges within personnel spaces, while visual cues are used for distant ranges (El Jamiy & Marsh, 2019). Proprioceptive cues include monocular and binocular vision, while visual cues assess the relative size of objects at different distances. When accessing objects at distant ranges, humans typically underestimate distance from an egocentric perspective, or when viewing from their location (El Jamiy & Marsh, 2019).

When employing proprioceptive cues, each eye receives different images in a scene, and the brain employs convergence. In the convergence process, the brain can determine depth.

Humans determine depth with one eye (monocular vision) through visual cues. This is accomplished by assessing the relative size of objects at different distances. Outside, and beyond 100 m, this is identified through changes in visibility due to the "degree of transparency of the atmospheric layer" (El Jamiy & Marsh, 2019, p. 710). Furthermore, the farther an object is from an observer, the more object outlines appear blurred.

In the binocular vision context, depth is determined between two objects using stereopsis, which is based "on the differences between the retinal image of the left and right eye" (El Jamiy & Marsh, 2019, p. 708). There is significant disagreement on the effect that binocular vision has at distant range, as some researchers believe it has limited to no effect beyond distances as close as 2 m, as the convergence angle shrinks to zero at certain distances. On the other hand, some researchers believe it supports perception up to 40 m (El Jamiy & Marsh, 2019).

### 3. Depth Cues Deep Dive

Dynamic cues include elements of vision we have discussed, plus the incorporation of angles. This is grounded in the fact that different cues have different angles of convergence when considering binocular vision (El Jamiy & Marsh, 2019). A series of cognitive sub cues are employed to determine the position of a subject within a field of view. These cues are:  Perception/adjustment, comparison, judgment, and description.

The definition of the perception/adjustment cue is when external factors affect the user's knowledge of the environment and the virtual object. The user must understand the distance between he/she and the object, and the distance from the user to the object once it has moved. An example of the comparison cue is when one object is compared to another. The judgement cue is employed when the user estimates the distance between the user and an object by comparing a well-known example, such as a football field. A description cue occurs when a scene is described to determine a metric. It is vital that the types of cues do not conflict with each other to ensure consistency.

A great way to understand the application of cues in virtual environments is by comparing the same scene in a real and virtual environment. When a same real-world scene is viewed in virtual reality, test subjects reported different distances between the same objects. Researchers evaluated the efficiency of distinct types of in-depth cues to understand this phenomenon. During the evaluation, the researchers evaluated depth based on the test subjects egocentric estimations (Fukusima et al., 1997). Egocentric distance perception must be considered by users assessing depth at distant ranges. The cues discussed provide insight into how both real and virtual cues can be employed to aid in fooling humans of a perceived depth.

## 4. Technical Tools and Solutions

There are many tools to enable target or object selection at ranges. One is gaze, where a target can be selected by the device when the user gazes at it for more than one second. Another tool is the use of depth cues within a scene. While our research does not focus on target selection, these tools may enable easier identification of distant VEs by automatically highlighting VEs when the user gazes towards them.

Traditionally, developers use a method of target selection where the user selects the target after gazing at it for a period of time. This works for a stationary observer and target. Researchers explored three approaches. One is the Move-Move, the second is the Stay-Move, and the third is the Move Stay. In order to simplify this, the user and target move, or either the user or target moves (Matsumoto et al., 2017). This research was completed using a HoloLens, and the range to the target remained the same. The researchers employed two different selection methods, one where the target stays fixed after the user gazes, and the second is where the target stays within the user's field of view. The results were statistically significant in showing that both new selection methods improved interaction with targets.

The gaze selection research appeared to focus on solving issues concerned with targeted marketing. While this is radically different than military target acquisition, this research provides insight into how known target areas might be identified by the HoloLens, and algorithms may be able to analyze changes in unnatural versus natural shapes in the environment. This may aid in allowing users to identify distant targets, either in combat or training. This research provides exceptional insight into the potential to aid in VE identification at distant ranges.

## E. WORLD LOCK/GEO-LOCATIONAL ANCHORING

### 1. Background

World lock/geo-locational anchoring are critical to ensure the scene is consistent for each and every user, each time it comes within the user's FOV. Scene consistency is challenging at distant ranges as factors contributing to inaccurate rendering of VEs has exponential negative effects. To understand geo-locational anchoring, we must first understand spatial mapping. Spatial mapping maps the virtual digital geographic scenes to the physical space surfaces to allow for virtual fusion (Wang et al., 2019). This allows for the interaction of the real and virtual environments, for example, placing a virtual apple on a real kitchen counter. Spatial mapping consists of two phases: the first step entails spatial mapping of the physical space and all existing objects within that space. This is done by scanning the physical environment in which you plan to place virtual objects. The second phase is when the device constructs a physical network of the space by retrieving a triangulation network.

### 2. Spatial Mapping Methods

There are multiple methods which can be employed to conduct spatial mapping. To construct the spatial map of an outdoor environment, all MR users can employ a spatial mapping took kit, which allows users to customize spatial mapping to their need. Traditionally, for large spaces that support large scenes, a detailed grid analysis which encapsulates floors, ceilings, and walls is required.

### 3. Typical Spatial Mapping Steps

Real-world space is scanned using the depth camera. The IVAS scanning program assists the user in mapping the space. The spatial surface topology and query feature calculates the room topology and stores the calculations. This process allows the device to know where each object and wall is within the space. The spatial shape query interface employs the topology analysis which specifies each parameter of each shape. The object placement solver interface ties each object to a specific location within the map, and the device tags are internally generated that tie objects to surface such as the floor, wall, or ceiling.

### 4. Spatial Mapping Outdoors

When using mixed reality outdoors, the cameras are pertinent to identifying known objects or features discussed above. The camera must capture an image every few seconds to generate data or a holograph. It must reach back, either to a local or edge compute capability, to enable image generation. Image capture can be done using a cellular, Bluetooth, or wireless network. The IVAS program leverages all three modalities to enable network connectivity.

### 5. Current Use Case: Tourism

A growing use of augmented reality (AR) outdoors is in the tourist industry. In Turin, Italy, the HoloLens is able to generate MR experiences for users. Users' general estimates of the images provided validation that the device can recognize large objects from approximately 50 m away, then generate information about the object (Praschl et al., 2018). Examples include retexturing or recoloring of actual buildings, information such as building names placed over a building, or the virtual re-construction of a ruin. Furthermore, the device generated a 3D virtual reconstruction of a ruin. The pictures in the academic paper appeared to be from 50 m away (Debandi et al., 2018). It should be noted that the tourist application of HoloLens is less challenging than the tactical military application because military training environments are either uniform in nature or completely random. In tourist environments, often the device is searching for a unique, distinguishable structure or object. During the tourist-based application of HoloLens, quick changes to lighting, such as quick transitions between clouds and sun light, affected image stability. This is a known issue, especially under cloudy conditions, or at dawn or dusk. A suggested solution is to employ model-based tracking rather than image based tracking (Debandi et al., 2018).

There are several other factors that can affect spatial mapping quality. These factors include uniform surfaces with no defining features, the placement of new objects within a scene, or removed objects. Other challenges include the failure to capture all major physical objects during the spatial mapping of an outdoor operating environment., which may affect the physics of VEs. One example would be a ledge that is positioned behind a taller ledge. If the ledge is not captured during the spatial mapping, an object such as a ball may not bounce off the shorter ledge. Another outcome is that the holograph will not navigate the scene properly. For example, if you fail to scan a parked car in your scene, a 3D human holograph will walk through the physical car. This issue may also affect occlusion, as the holographic person standing behind the car may have his/her legs appear in front of the car.

### 6. IVAS Spatial Mapping Approach

The IVAS program employs a unique spatial mapping variant for outdoors. Some aspects of the technology are still under development as of late 2021. The concept is similar to the spatial mapping techniques used in an indoor environment. The person capturing the spatial map walks through the environment wearing a HoloLens II, which uses a long throw, low frequency (1-5 frames per second) far depth sensing camera. The HoloLens II camera generates an occlusion mesh and head tracking map. It does not use the global positioning system (GPS), rather a relative coordinate system. The location you begin capturing the scene is the same location where you start (0, 0, 0). The ceiling is assumed to be a standard height. The head tracking map allows the system to track its position and orientation relative to origin. This is referred to as a world lock spatial coordinate system (Zeller et al., 2018). The system uses a voice wizard to guide the trainer through the system. After the mesh is collected, it is processed and converted to plains.

### 7. IVAS Spatial Mapping Challenges and Potential Solutions

There are ways to address some common issues found after a scene is spatially mapped and meshed. Holes, or areas of the physical world which were not mapped, can cause computational issues. Some holes are filled in automatically, and if scanned areas do not reflect the real world, you can re-update the scan. Filling holes digitally has challenges, as some holes may be intentional to lessen computational requirements. Outdoors, bright lights or moving objects can cause blurs in the spatial map. This is referred to as "hallucination" by Microsoft. This can lead to increased computational cost as ray casting will be challenged (Zeller et al., 2018). Occlusion may also be affected. Correcting these issues can be mitigated by bundling ray cast, or algorithmically filling them in the surface mesh. Another solution is through plane finding, which identifies "play areas" or planes which are most suitable to holographs. This may be helpful in the outdoor, military use case, but only to a limited degree compared to traditional mixed reality use cases.

## F. MIXED REALITY TRACKING

### 1. Background

Positional tracking is pivotal in enabling mixed reality devices to accurately place and maintain holograms relative to the actual world. It enables users to design a scenario or game, turn off the device, then come back a day later and find the hologram in the same location. The placing of virtual objects is achieved by using spatial anchors, which enables them to be world locked, which enables through occlusion. Occlusion enables virtual objects to be blocked by a real object, or vice versa. This is achieved using a variety of methods. These methods include Global Positioning System (GPS), outside-in, and Simultaneous Localization and Mapping (SLAM). The combined approach is called the Attitude Heading Reference System (AHRS) developed by Advanced Information Systems and Technology at the University of Applied Sciences Upper Austria. It assesses the difference in orientation between video, gyroscope drift, and GPS (Praschl et al., 2018). Currently, orientation positioning capability is not well supported by hardware organic to most HUDs. Key generic approaches to tracking found in Praschl et al. paper is discussed below.

### 2. GPS

GPS enables the device to gain locational understanding outdoors, but consistent satellite connection is required. Researchers have used GPS, rover, and a real-time base station beacon system to achieve enhanced precision outdoors. This GPS method works over long distances in European tourist hot spots. These distances are similar to those required to support outdoor military training. The primary application of GPS, enhanced with sensors such as advanced inertial measurement units with accelerometers, is called "dead reckoning." Dead reckoning allows velocity to be calculated with an approximation of the integral (Praschl et al., 2018). Position can be calculated using the new and previous velocity. The challenge in the military context is the managing and setting up supporting equipment, such as navigation beacons and wireless networks, which can be barriers to training/use.

#### 3. Outside-In

Outside-in tracking uses external systems to aide in navigational tracking (Praschl et al., 2018). Typically, this is done with QR code markers or tape which act as fiducial markers when using the HoloLens. An example of outside-in tracking is when Bluetooth beacons are used in conjunction with the device accelerometer to determine velocity and distance moved. Other examples include calibrated video cameras which aide in determining movement within an operational space.

#### 4. Simultaneous Localization and Mapping (SLAM)

The algorithm draws conclusions about device location using internal device sensors such as accelerometers and gyroscopes. This can be aided by GPS systems.

#### 5. Remedies

Studies using infrared markers and additional cameras have been used to aide in locational tracking (Praschl et al., 2018). This technique has been used in the IVAS program, but was deemed impractical as the device is used for low-light environments. Furthermore, during daylight, the effect of infrared is limited. These studies also used external servers and positioning. The IVAS HUD cannot use external sensors, but has a broader array of sensors which may be applicable. The IVAS HUD employs a GPS capability that can be employed to aide in location tracking. It should be noted, the sensor-based approach uses an advance IMU which is not internal to the HoloLens or IVAS HUD. The research discussed below examined image orientation and positioning using Microsoft HoloLens while driving a car. The users were presented fixed images and moving 3D virtual humans. During positioning test, the users wearing HoloLens would view and image, move, away from it, then return. They would then measure the displacement of the image.

The first approach taken by the researchers was image-based orientation. It calculated changes in orientation around an axis, then simplified to a translation. All rotational changes, r, are transferred to the z axis orientation, then x-axis, considering the camera's vertical and horizontal fields of view. This approach was effective, but only supported orientational movement within 5 degrees.

The second approach used was sensor-based orientation. This used an algorithm which consumes data from the AHRS. It leverages video camera images, accelerometer, and GPS positional data to assist the device in accurately placing virtual objects in space. A major advantage of AHRS is it has on-board data processing capabilities (Praschl et al., 2018). However, we do not know the absolute capability of the IVAS system and whether it can perform those calculations at the required speed for effective tracking. Early data captured by government engineers have determined this is possible, but further research must be completed to validate their findings. The orientation results for the sensor approach while wearing the HoloLens were stable, but they did require some time for the sensor to settle, allowing for the image to stabilize.

To complete the assessment of outdoor capabilities, a hybrid approach was employed by researchers to enable calculations "…to be merged using a weighted average method" (Praschl et al., 2018, p. 130). In order to avoid skewed results from a single outcome, the results are blocked within ranges. Data from single approaches are blocked based on orientational ranges. Sensor -based approaches are estimations, and therefore too inaccurate when only minor changes are present. Due to errors in the data, it may end up being useless in the case of minor changes. Image based approaches yield less errors, but require increased processing cost. Weighting the two approaches, then combining alleviates some of these challenges. Furthermore, different scenarios that challenge, or do not challenge positional tracking can yield inaccurate results from the data.

The last approach explored is the rover and base station approach. It uses a Real Time Kinematic (RTK) which enhances GPS accuracy below that of the standard 5 m. This approach uses a station to correct the data of a moving rover. This method can be applied in a military, ground forces context, but is most useful to mounted units which have vehicles to mount this equipment. The focus of this research is to implement believably accurate outdoor images for servicemembers to engage in a dismounted manner. Therefore, the rover and base station approach may provide unnecessarily accurate data. This approach can be applied to further research in this area as it will eventually require mobile networking. During this approach, the researchers used an Emlid Reach RTK kit. The GPS beacons used a transmission control protocol/ internet protocol that allowed the HoloLens to receive messages from the kit. The network is powered by 4G mobile routers. This compliments proof of concept network testing with IVAS Squad immersive Virtual Trainer (SiVT) which found 4G networks were most effective for the system executing military operations in urban terrain. This also means that the IVAS network package, which is mounted and includes 4G, can potentially aide in supporting IVAS SiVT for outdoor purposes. This approach was tested for its ability to provide positional accuracy. To execute this test, a person moved to several pre-defined positions, and then returned to the starting point to evaluate a virtual image where the mean accuracy was 30 cm.

The approaches discussed employ Microsoft HoloLens, Unity, and C#. An external server was employed to assess high-cost computations. The secondary computer supporting computations employed a "…computer vision framework based on the OpenCV Java wrapper by OpenPnP (OpenPnP, 2017) in combination with the Spring Framework (Pivotal Software, 2018)" (Praschl et al., 2018). The software architecture allows for either the accelerated data, image, or hybrid methods for calculating positional orientation. Also used are GPS–RTK receivers, which enabled average tracking accuracy up to 30cm (Praschl et al., 2018). It should be noted that this research was tested by mounting a HoloLens II in automobiles traveling on roads and in parking lots where moving holographic images were simultaneously successfully generated. The military application will typically not be tested under these speeds. The dismounted application of IVAS SiVT must support much slower movement, but potentially more jolts and sudden actions. During this research effort, a hybrid approach will be explored using the sensor-based approach combined with reconciliation of the sensor-based device map and GPS data.

The tracking approaches discussed provide multiple examples of how HoloLens tracking can be aided to enable outdoor use. The primary approaches recommended by researchers include an image-based approach, a sensor-based approach, and a hybrid approach. These approaches provide insight into approaches which may enable outdoor training using IVAS.

## G. HEALTH AND SAFETY CONSIDERATIONS

Cybersickness, fatigue, and stress are the major concerns for Augmented Reality (AR)/MR users. This must be considered in the experimental design. There are limited studies which purely focus on MR and cybersickness. The challenge with MR is users typically do not experience cybersickness symptoms which cause them to self-limit exposure (Hughes et al., 2020). In other words, the on-set of cybersickness symptoms related to MR occur after using the technology. The primary symptoms of cybersickness are nausea (N), disorientation (D), and oculomotor (O) issues. In VR, these symptoms are typically manifested in with N > O > D (Kennedy et al., 1993). In MR, they are manifested differently, beginning with O>D>N (Hughes et al., 2020).

Stress is tied to the response Automatic Nervous System (ANS) which regulates the functions of internal organs. Heart rate, sweating, and temperature are specifically known to be regulated by the ANS. Changes in sweating, skin temperature, and heart rate are signs the ANS is responding to stress. Through these measurements, stimuli in a VR training environment are shown to increase stress levels (Cho et al., 2017). Consequently, when researchers studied job applicants who trained using VR prior to interviews, their stress levels were measured lower than those who had not prepared using VR (Cho et al., 2017). During pilot and the observational study, users can be made aware of symptoms tied to these symptoms and notify test researchers if they reach a harmful level of discomfort.

The greatest safety concern is cyber sickness as it is highly correlated to visual-vestibular conflict. Cybersickness occurs as the brain’s vestibular system works to integrate virtual scenes with actual movement (Gallagher & Ferrè, 2018). Displaying to the user a myriad of sensors, devices being tracked, and other VEs increases the potential for the user to develop cyber sickness. This may be due to increased chances for sensory conflict between the visual and vestibular system (Nichols & Patel, 2002). This can potentially be mitigated by introducing virtual objects which users are familiar, or by decreasing actual movement velocity. Screen quality, flicker, and frame rate are also associated with cyber sickness, specifically wide field of view devices. The IVAS HUD field of view is wider than the field of view to which most AR users are familiar, so virtual objects presentation should avoid the peripheral field of view (Gallagher & Ferrè, 2018). A less possible safety concern is oculomotor symptoms which are associated with sustained, fast movements, such as driving a virtual car at high speeds. While this scenario is less likely, quick movements may generate oculomotor discomfort, particularly among females. Specifically, young males are less prone to cyber sickness, while older females are most prone to cyber sickness (Nichols and Patel, 2002). Consequently, pilot testing should include females in the sample population, to include middle age to older females. This will ensure all personnel can fully utilize the capability. Sitting in a chair while wearing a VR headset portraying a scenario which the user feels he/she is moving may induce cybersickness as the body is not moving, but the mind perceives movement. Conversely, AR systems which allow users to visualize their actual surroundings, typically has less sensory conflicts (Stanney et al., 2020).

## H. RESEARCH QUESTIONS

There are two research questions and an exploratory question based on variables that were observed to determine their effectiveness in improving visualizations of outdoor VEs.

**Research Question 1**: To what extent can employing global positional data be used to support navigational mesh development to enable placement and identification of 3D virtual entities at distances of 50, 100, and 200 m?

Prediction 1:

1. 90% of subjects will be able to identify 3D virtual objects under most conditions at ranges less than or equal to 50 m.

2. 75% of subjects will be able to identify 3D virtual objects under most conditions at ranges less than or equal to 100 m.

3. 25% of subjects will be able to identify 3D virtual objects under most conditions at ranges less than or equal to 200 m.

Hypothesis 1: Application of GPS in tandem with MR will enable users, on average, identification of 3D virtual NPC's and objects in the viewer 90% of the time at distances of 50 m, 75% of the time at 100 m and 25% of the time at 200 m.

**Research Question 2:** Can employing animation of 3D VEs enable improve identification of objects at ranges greater than 20 m?

Prediction: Animation of 3D virtual objects will improve positive identification scores compared to objects at the same range, 90% of the time.

Hypothesis 2: Across subjects, animation of 3D entities at distances up to 200 m within the parameters defined, on average, will improve identification when compared to similar objects at ranges, 90% of the time, $\mu > .90$.

**Exploratory Question 1:** To what extent can adjusted light levels of 3D entities support identification at ranges of 20–300 m?

# II. PILOT TESTING

This chapter documents and explains the steps the research team took to design and develop the study. This chapter covers the four phases of research, discussing the design and challenges within each phase. Phase 1 focuses on preparation, which includes the logistics, legal/regulatory approval, background, and challenges. Phase 2 focuses on hardware and software testing, changes to the study design, and challenges.

## A. PHASE 1: PREPARATION.

The primary device we used is the Microsoft HoloLens II. Although we considered using the IVAS HUD, it lacks a depth sensor, requiring the use of external sensors to ensure positional accuracy, and thus was not suitable for this experiment. Employment of the IVAS HUD contains more research and logistical challenges as the major components include the HUD, the surrogate weapon and instrumentation, and potentially network equipment. Furthermore, the complementary software and basic tutorials must be provided by the program manager. This phase was expected to be completed in early to mid-October, but the acquisition of the IVAS HUD software access to allow support of 3D party vendors was not approved until January. Consequently, in December our team decided to pursue the research utilizing the VR Rehab HoloWarrior and HoloNav technology as it allowed us to immediately commence pilot testing.

## B. PHASE 2: PILOT TESTING.

We conducted pilot testing in three sub-phases: familiarization with the vendors technology and our research goals, initial software testing and updates, and positional software improvements. Each sub- phase of pilot testing consisted of a 1– to 2–week development sprint, followed by 1 to 2 days of experimentation. Phase 2 overlapped with Phase1 and began in late November with software tutorials and capability updates. The initial part of this phase entailed designing inventory and familiarization with equipment and software. Pilot testing took place in January through early March. It employed fellow researchers to refine the capability prior to the observational study in Phase 3.

### 1. Phase 2a, Familiarization

Familiarization began in early December as we attained the equipment and HoloWarrior software from VR Rehab. Visits between myself and the VR Rehab team took place at their office in Orlando. The visit consisted of a technology demonstration and familiarization training. The meeting also allowed for a common agreement and understanding of research goals. A second meeting took place at the Synthetic Training Environment (STE) Cross Functional Team (CFT) laboratories in Orlando. It created a clearer understanding of our research goals within VR Rehab.

The VR Rehab HoloWarrior software and hardware have multiple components. The software consisted of an operational and scenario design mode. It also included features for ground and aerial unmanned vehicle inputs. We employed the operational ground UAV setting as it incorporated a library of both VEs/targets, and standard military graphical control measures. It also included the ability to employ GPS, and manually modify light levels for VEs. The hardware included a visor and a sun shade which allowed most virtual objects at ranges less than 100 m to be viewed in the morning and afternoon without the need to manually modify light levels.

Originally, we struggled to navigate through the software interfaces without a Microsoft X Box controller, which enabled quicker navigation. This is primarily because it allowed the user to navigate back to the main menu using the HoloLens II, which was not available with gestures. This required multiple meetings with VR Rehab software programmers, and research on importing the software. Once basic familiarization was complete, several bugs were discovered during this process. The bugs are listed below:

1. There are two basic modes, operational, and mission rehearsal. The operational mode initially did not work as the virtual terrain background remained in the scene. This was corrected by disabling the background in operational mode.

2. The GPS location, when placed in operational mode, was continually 100 m offset from the actual location. This was remedied by updating the

software to incorporate the specific GPS device and supporting Bluetooth signal.

3. The compass was 90–180 degrees in the wrong direction. The compass was adjusted using an X-Box controller and physical compass.

### 2. Phase 2b, Software and Positional Testing

Software and positional testing took place in indoor and outdoor environments. The intent of the indoor pilot testing was to modify existing virtual models and hardware settings. Each iteration included scenario design, which was completed on a gaming laptop computer, and utilized terrain maps to place each virtual object. The indoor pilot testing introduced controlled factors such as varying light levels. It also examined positional accuracy within large indoor spaces such as gyms or auditoriums at distances up to 100 m. This design allowed for relatively rapid correction of technical issues. Once complete, the models were tested outdoors to introduce a more diverse set of confounding variables. The goals of outdoor pilot testing included assessing outdoor ranges supported within each software build, and visual quality of 3D entities outdoors. The phase also determined occlusion challenges, and virtual NPC mobility. Assessments were up to 300 m. During Phase 2b, virtual models of personnel or mobile objects such as vehicles were refined to support initial assessments.

Due to the nature of software releases, we focused on VE development and movement, without having a fully functional GPS capability. This was achieved through manual placement and input of GPS locations of entities. The location of VEs did not remain consistent. Consequently, the inaccuracies and time required to set up the MR environment delayed mature pilot testing until the GPS capability was corrected.

### 3. Phase 2c, Formal Pilot Testing

Formal pilot testing took place in late February and early March. Formal pilot testing served as a rehearsal for the actual observational study. It began outside of Watkins Hall, on the NPS campus, moved to the outside, southwest corner of Hermann Hall, then to the southeast corner portion of campus near Spanagel Hall. Each site was chosen to ensure that subjects had a clear line of sight out to at least 200 m and included diverse landscapes. Considerations included shadowing effects, vegetation, and urban clutter such as garbage cans. This allowed for understanding of potential technological and logistical challenges. It also validated the requirements needed to enable the use of two HoloLens II devices in vicinity of Hermann Hall. During this testing, virtual object placement and the subject's vantage point at each location was refined. One observational test site, the roof of Spanagel Hall, had to be moved to the ground level because Spanagel Hall has several antennas and electromagnetic equipment on its roof which prevented the acquisition of a GPS signal. Pilot testing was completed when the research team verified each step of the testing process, and the software, was ready to support testing at three sites, over the course of one hour.

## C. SUMMARY

The final observational test design allowed for eight total treatments viewed by 20 test subjects during March 2022 using a HoloLens II. The software employed was the VR Rehab HoloNav, and the HoloLens was augmented with a visor and sunshade to reduce light levels. This observational test consisted of three locations on the NPS campus visited by each test subject over the course of an hour. The environment allowed for multiple natural environmental factors to replicate those commonly found in combat.

# III. OBSERVATIONAL STUDY METHODOLOGY

This study employed the single-group with continuous treatment. The NPS IRB (IRB # NPS.2022.0021-IR-EP7-A) approved this study.

The study design employed an observational study with 20 participants. The observational study typically took approximately one hour per participant and focused on the user wearing the HoloLens II outdoors. At each testing site, a series of two to three images were displayed at ranges between 50–200 m.

The goal was to assess if the objects can be determined by users, and how clearly, they can be determined.

## A. STUDY PARTICIPANTS

The study's target population are warfighters from the maneuver and intelligence fields. People were excluded from participating in the study if they were not fluent in English to avoid the difficulty that would arise in interpreting the visual descriptions, were prone to cyber sickness, and/or whose vision acuity test yielded less than 20/20 vision with correctable lenses.

Participants for the study were recruited from within the Computer Science and Systems Engineering departments via email. Each participant was asked to volunteer one hour of their time to complete the study.

There were 20 total test subjects' participants, 19 of whom are active-duty military, and one who is serving in the Naval Reserve. Table 1 shows the descriptive statistics for the participants. The experience and diversity of the test subjects is almost ideal, though greater representation of females which reflects the armed services population is preferable due to differences in sensory perception (Barber, 2020).

Table 1. Demographic descriptors

| | |
|---|---|
| Age | mean = 34.1, s = 4.447 |
| Gender | Male:18, Female: 2 |
| Service | Army: 8, Navy: 4, Marines: 7, Coast Guard: 1, |
| Years of Service | mean= 11.5, s = 5.05 |
| Military Specialty | Aviation: 4, Maneuver: 7, Sustainment: 4, Intelligence: 2, Fires: 1, Engineering: 1, Communication: 1 |
| Enemy Identification Training | 16 |
| AR/VR Experience | 18 |

## B. IDENTIFICATION TASKS AND SCENARIOS

The sites allowed for a diverse set of variables to be considered at two—three different ranges (50, 100, 200 m). Each site presented at least two of the following images: HMMWV, jeep, a Soldier, animated civilian in a fixed location, and a building. The max range was intended to be 300 m, but occlusion and varying differences in elevation beyond 200 m made it almost impossible to lock the virtual object to the ground. For example, when the scenario was tested, the object would appear 10 feet above the ground, then the next time the scenario was tested, the object would appear below the ground. For each image, the user was asked to determine the type of object portrayed in the image, how confident they were of what type of object was portrayed, and if they can identify a defining feature. The intent is to support statistical blocking if required. Participants were debriefed upon completion of the study.

Visual model presentation consisted of dismounted personnel, transport vehicles, and Alaskan tents. The size ratios were fixed based off the templated position of the test subject during the scenario design. This ensured the general position of each VE/object was realistic. The entity options include people, buildings, and vehicles.

There were three scenarios employed in the testing. A map of the NPS campus and each scenario location is found in Figure 1.

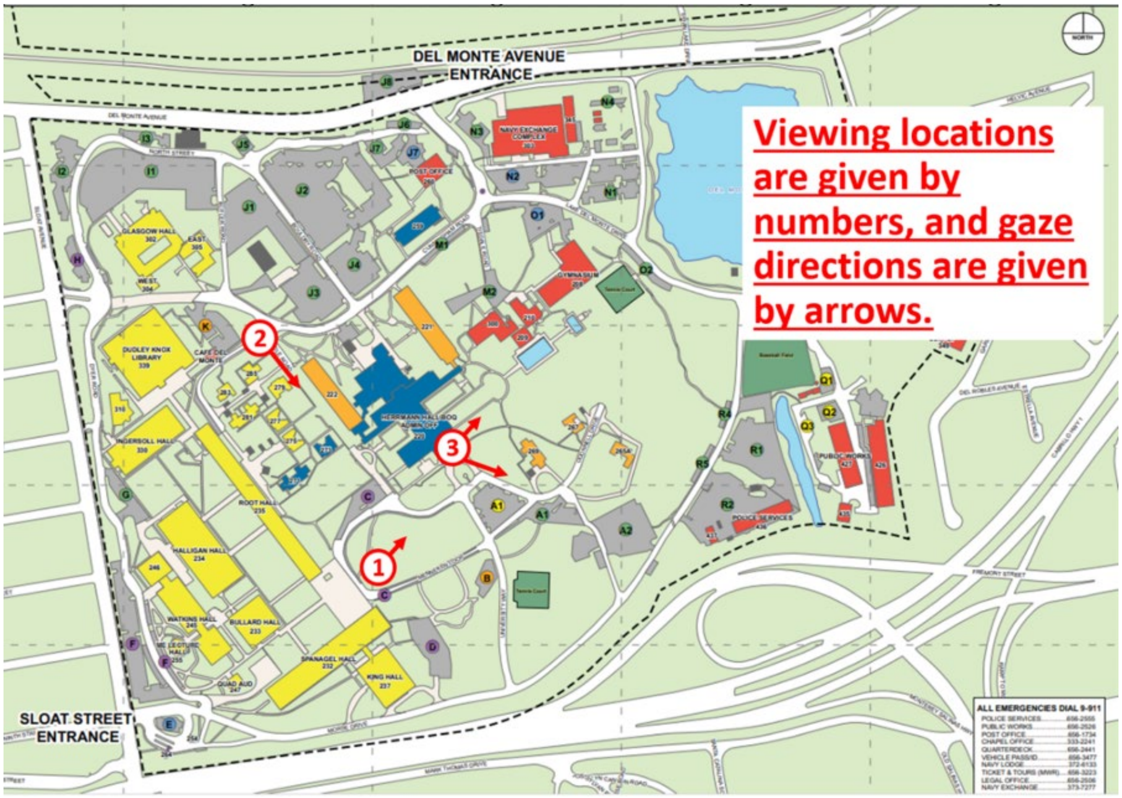



Figure 1. NPS campus map with the three scenario locations shown by number

1. Scenario 1 (Figure 2) was located on the southwest side of Hermann Hall and included two virtual objects. The test subjects viewed the scenario looking slightly northeast. The first virtual object was a man who was walking in place on a sidewalk, approximately 50 m from the test subject, wearing traditional Middle Eastern clothing. The second virtual object was a tan HMMWV parked in the grass, approximately 100 m from the test subject, who viewed the vehicle from its side. The environmental features included trees, dense shade, an open field, and a road.

Figure 2. Scenario 1, Hermann Hall, facing north

2. Scenario 2 (Figure 3) was located at the northwest side of Hermann Hall along a blocked off road and three virtual objects were visible. The test subject viewed the scenario looking southeast. The first virtual object was a man who was walking in place on a sidewalk, approximately 50 m from the test subject, wearing traditional Middle Eastern clothing. The second virtual object was a tan Jeep parked along an unused road, approximately 100 m from the test subject, and offset to the left of the man walking down the sidewalk. The third virtual object was 200 m from the test subject, and offset to the left of the Jeep, was a green Alaskan medical tent, with a red cross on the front. All virtual objects were viewed from their front by the test subject. The environmental factors included consistent shade provided by Hermann Hall and the trees on each side of the road, and little shade between the test subject and the first virtual object, 50 m away.

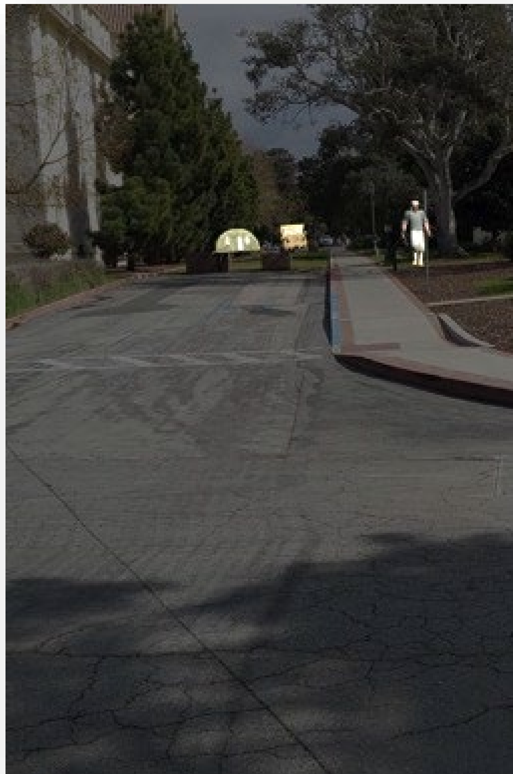


Figure 3. Hermann Hall, facing southeast, Scenario 2

3. Scenario 3 (Figure 4) was located to the north of Hermann Hall and three virtual objects were visible. It was viewed from the fourth-floor tower of Hermann Hall. The test subject viewed the scenario looking northeast, then to the southeast. The closest virtual object was an inanimate soldier wearing military gear and holding a weapon approximately 50 m from the test subject. The second virtual object was 100 m from the test subject, and offset to the northwest, was a green Alaskan medical tent, with a red cross on the front. The third virtual object was a tan Jeep parked along an unused road, approximately 200 m from the test subject, and offset to the northeast of the tent, and was placed upon the roof of a building. The environmental factors included shadowing provided by trees onto the virtual objects, standing water, and light washout from the sun.

Figure 4. Hermann Hall, facing north, Scenario 3

## C. SURVEYS

The study used two surveys: a demographic survey and a post-task survey (see the Appendix). The intent of the surveys was to gain a greater understanding of the research audience background, to identify health concerns, and insight into their experience.

### 1. Demographic Survey

The demographic survey collected basic data concerning the participants' age, gender, military service, and AR device usage experiences. This survey allowed the research team to conduct a final screening of the participants to ensure they did not meet the exclusion criteria. It also provided insight into the background of each user, and how it may be related to their feedback concerning image visualizations. Participants recorded their answers on paper, and they were stored in a secure container.

### 2. Feedback or Post-Test Survey

This survey attained user feedback on how they identified each object, and also their professional opinion regarding the technologies ability to support outdoor training.

## D. EQUIPMENT

This study used one computer and one HoloLens II device.

1. Desktop computer: The computer used for this study is an older Alienware Aurora R4 with an NVIDIA GeForce GTX690 video card was used to input survey data.

2. HoloLens II device: The HoloLens II utilized Virtual Reality Rehab (VR Rehab) HoloWarrior software and HoloNav system. The system is supported by an external global position system (GPS) with a Bluetooth wireless connection. It also employs a sun visor and attachable sun glasses to dim the effects of bright sunlight.

## E. PROCEDURES

The detailed procedures/flow of study went as follows:

1. The device and equipment had to be validated it was in working condition. This required to researcher to arrive thirty minutes early to ensure all batteries were charged.

2. The subject arrived at researchers' offices in Watkins Hall. Upon arrival, the subject reviewed the consent form, and signed. Once complete with the consent form, the subject filled out the demographic survey.

3. The subjects' vision was validated using a standard vision test to ensure 20/20 vision. This ensured the subjects ability to identify, or not identify an object was not due to the subjects near/far vision.

4. Upon completion of the vision test, the researcher and subject walked to observational test site 1 southeast of Hermann Hall, to allow execution of the first scenario. This took approximately 10–20 minutes as signal interference from nearby antenna's made it difficult to attain GPS signal. It took the researcher approximately 10–15 minutes to open the scenario and acquire GPS signal, then five minutes to actually complete the scenario.

5. When the first scenario was complete, the researcher and subject walked to the observational test site 2 at the southwest side of Hermann Hall. This took approximately five minutes. At test site 2, the second scenario was

executed. It took approximately 5–10 minutes to open the scenario, and five minutes to complete the scenario.

6. Once the second scenario was complete, the researcher and subject proceeded to the balcony overlooking the NPS campus flag pole and Roman Plunge in the fourth floor to the Tower Room. The scenario took five minutes to open and adjust, and five minutes to complete.

7. Upon completion, the group then walked back to Watkins Hall, which took five minutes. At Watkins Hall, the post-test scenario was completed, and results were locked in a file cabinet.

# IV. RESULTS

This chapter is composed of the following sections: Data preparation, statistical analysis, preliminary analysis, hypothesis related testing results, demographic and post-test survey results.

## A. DATA PREPARATION

This study incorporates two sets of data. This first set of data comes from the demographic survey and post-test survey. The second set of data is derived from subject feedback during the observational study. Survey data and user feedback were inputted into Microsoft Excel and checked for errors prior to being exported to JMP Pro 15.1 for statistical analyses.

Participants completed the demographic and post-test survey using pencil and paper. The document was developed using Microsoft Word. The researcher recorded subject's verbal comments onto paper. Demographic, post-test, and observational test study data was transferred to Excel at the end of each day. The data was then transferred to JMP for statistical analysis. Each subject was provided a number to mask their identity.

## B. STATISTICAL ANALYSIS

The statistical methods used for hypothesis and exploratory analysis are the Chi-square tests of homogeneity and independence. The Chi-square methods allowed for testing of Likert scale ratings from user feedback (ordinal variable) by distance (ordinal variable) and scenario type (categorical variable). An alpha level of .05 was used for all hypothesis testing. The data sample is random in respect to military background and experience. Assumptions for the Chi-square Test were checked. Because the user feedback data did not meet the expected values assumption (see Figure 5), data from the Likert ratings was condensed to two rating levels, visible and not visible. Original Likert ratings of 1–3 were classified as visible, original Likert ratings of 4–5 were classified as not visible. The original Likert ratings can be found in Figure 5. After this reclassification, the assumptions and conditions were met.

## C. PRELIMINARY ANALYSIS

The preliminary analysis focuses on the descriptive statistics for each object in each scenario. The same type of VE, such as an animated human, is found in two scenarios. If the same VE occurs twice, it is only referenced for a specific scenario, rather than multiple.

### 1. Visibility Ratings by Scenario and Distance

A comprehensive breakdown of subjects' ability to identify virtual objects outdoors is found in Figure 5. It captures subject feedback by distance and scenario. There were three distances (50, 100, and 200 m) and three scenarios. In Scenario 1, there were only two VEs for identification. Scenario 2 and 3 allowed for three VEs to be potentially identified. The best performing scenario was predictably at 50 m, and in Scenario 1, with a mean = 1.2. The worst performing scenario was at 200 m (mean = 3.8). The mean best scenario (Scenario 2) performance at 200 m was 65% worse than the worst performance at 50 m (Scenario 2).

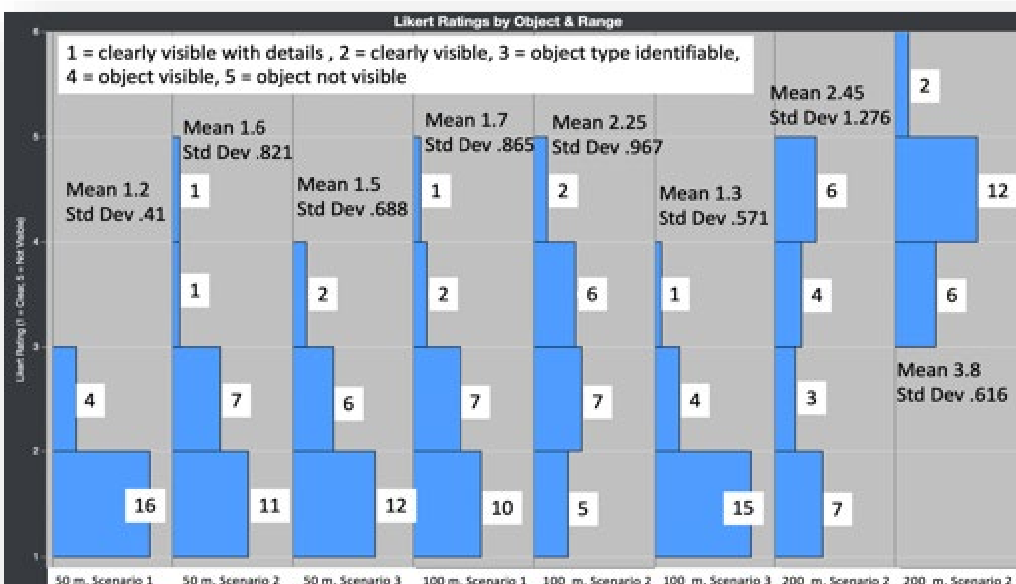
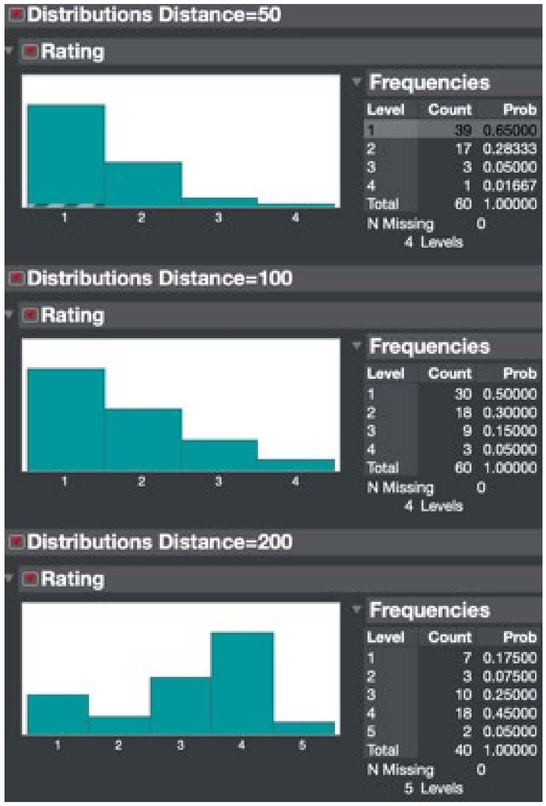
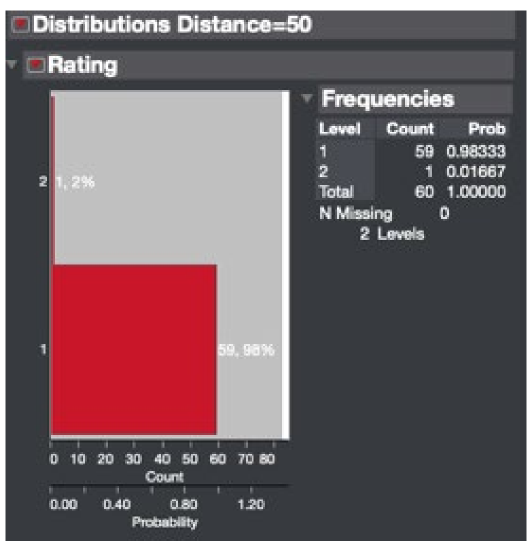



Figure 5. Likert ratings by object and range




Frequencies reflect the number of choices by Likert Ratings 1–5. Count indicates number of selections, and "Prob" indicates percentage of subjects who made selection.

Figure 6. Frequencies for Likert ratings 1– 5 by distance

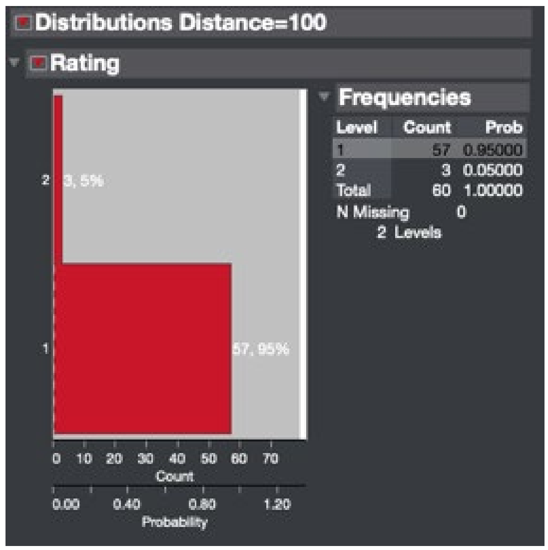



Participants identified virtual objects visible (red) and unidentifiable (grey)

Figure 7. User outcomes for VEs at 50 m

### 2. Visibility Results by Objects

The VEs placed at 50 m were two civilians wearing Middle Eastern-style clothing walking in place and one service member wearing camouflage. There was one VE per scenario at 50 m. There was a total of 60 observations, and 59, or 98.3% identified the VE. Scenario 2 had the poorest score (mean = 1.6), and Scenario 1 had the best score (mean = 1.2).

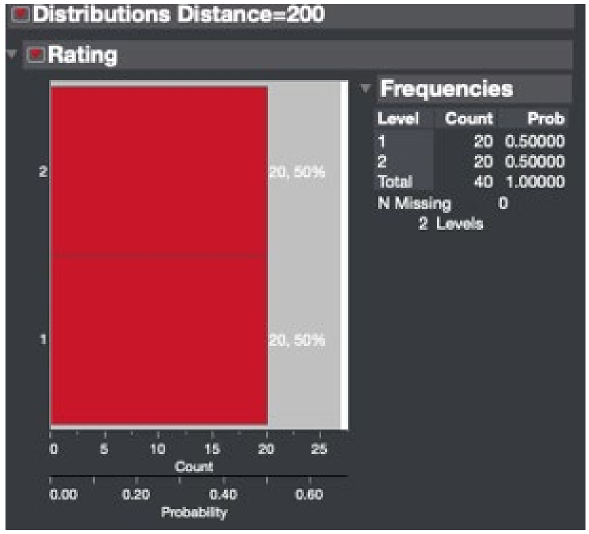



Participants identified virtual objects visible (red) and unidentifiable (grey)

Figure 8. Likert ratings frequencies for visibility of VEs at 100 m

VEs placed at 100 m included a HMMWV, a Jeep, and a medical tent. The probability of identifying the VE was 95%, and Scenario 3 had the best mean score (medical tent) at mean = 1.3. Once again Scenario 2 had the highest mean, or poorest score, at mean = 2.25.

The VEs at 200 m were only found in scenarios 2 and 3. The VEs placed at 200 m were a medical tent (Scenario 2) and a Jeep (Scenario 3). There was a 50% probability of subjects identifying the VE, 45% difference from 100 m, and 48% difference than 50 m. The tent nor the Jeep were completely clear, but participants rated the VEs as clearer in Scenario 2 (mean = 2.25) than in Scenario 3 (mean = 3.8).




Participants identified virtual objects visible (red) and unidentifiable (grey)

Figure 9. Likert ratings frequencies for visibility of VEs at 200 m

## D. RESEARCH QUESTION 1

This section examines to what extent can employing global positional data be used to support navigational mesh development to enable placement and identification of 3D virtual objects at distances of 50, 100, and 200 m. The intent is to gain a greater understanding of the ability of GPS to assist in locking a VE to the same location consistently.

***Hypothesis 1: Application of GPS in tandem with MR will enable users, on average, identification of 3D virtual NPC's and objects in the viewer 90% of the time at distances of 50 m, 75% of the time at 100 m and 25% of the time at 200 m.***

To test the hypothesis, the team employed a Chi- square analysis and One Proportion Z Test at ranges of 50, 100, and 200 m. To generate the analysis, all scores three and below were assigned to one (identifiable object type), and all scores four or more were assigned a two (unidentifiable object type).

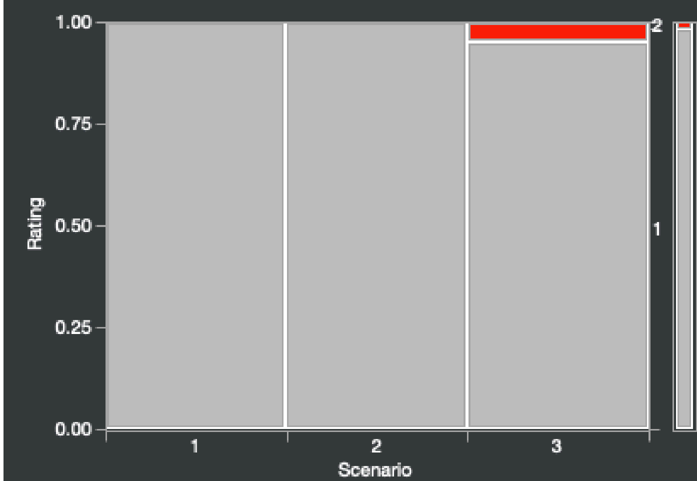
The analysis indicates that accurate positional data did not aide users' overall identification of objects in a statistically significant manner (Chi- square (2) = 2.231, $p < 0.3277$ (Figure 10). The benefit of the Chi- square analysis is limited as there is an almost perfect score, with 59 of 60 VEs identified. Data did not meet expected values count for Chi- square. Researchers then analyzed users' ability to identify VEs at 50 m. The results virtual object identification results were better than predicted ($z = 2.15$, $p = 0.0315$, 95% confidence interval (CI), 0.95 to 1.02). The null hypothesis at 50m is therefore rejected.

The second set of data analyzed was users' ability to identify VEs at 100 m. These entities included a HMMWV, Jeep, and a medical tent. The analysis indicates that accurate positional data did aid users statistically significant manner (Chi- square (2) = 8.279, $p > 0.0159$ (Figure 11). The benefit of the Chi- square analysis is limited as there is an almost perfect score, with 48 of 60 VEs identified. The One Proportion Z Test results yielded $z = .894$, $p = .3711$, and a 95% CI of .69 to .90. The null hypothesis at 100 m is therefore retained.

Last, subjects' ability to identify VEs at 200 m was analyzed. The entities included a medical tent and Jeep. The analysis indicates that accurate positional data did not aid users, but was statistically significant (Chi- square (1) = 17.261, $p < 0.0001$ (Figure 12). The One Proportion Z Test results yielded $z = 4.472$, $p = .00001$, and a 95% CI of .35 to 0.65. The null hypothesis at 200 m is therefore rejected.

**Contingency Analysis of Rating By Scenario Distance=50**

**Mosaic Plot**




**Contingency Table**

| Scenario | Count / Total % / Col % / Row % | Rating 1 | Rating 2 | Total |
|---|---|---|---|---|
| 1 | Count | 20 | 0 | 20 |
| | Total % | 33.33 | 0.00 | 33.33 |
| | Col % | 33.90 | 0.00 | |
| | Row % | 100.00 | 0.00 | |
| 2 | Count | 20 | 0 | 20 |
| | Total % | 33.33 | 0.00 | 33.33 |
| | Col % | 33.90 | 0.00 | |
| | Row % | 100.00 | 0.00 | |
| 3 | Count | 19 | 1 | 20 |
| | Total % | 31.67 | 1.67 | 33.33 |
| | Col % | 32.20 | 100.00 | |
| | Row % | 95.00 | 5.00 | |
| Total | Count | 59 | 1 | 60 |
| | Total % | 98.33 | 1.67 | |

**Tests**

| N | DF | -LogLike | RSquare (U) |
|---|---|---|---|
| 60 | 2 | 1.1156597 | 0.2194 |

| Test | ChiSquare | Prob>ChiSq |
|---|---|---|
| Likelihood Ratio | 2.231 | 0.3277 |
| Pearson | 2.034 | 0.3617 |

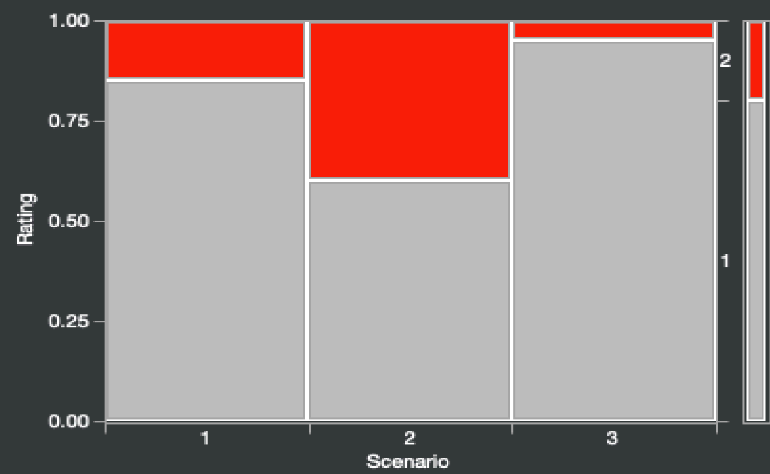
Warning: 20% of cells have expected count less than 5, ChiSquare suspect.

Participants identified virtual objects visible (grey) and unidentifiable (red)

Figure 10. Contingency analysis of rating by scenario and distance, 50 m

## Contingency Analysis of Rating By Scenario Distance=100

### Mosaic Plot




### Contingency Table

| Count / Total % / Col % / Row % | Rating: 1 | 2 | Total |
|---|---|---|---|
| Scenario 1 | 17 | 3 | 20 |
| | 28.33 | 5.00 | 33.33 |
| | 35.42 | 25.00 | |
| | 85.00 | 15.00 | |
| 2 | 12 | 8 | 20 |
| | 20.00 | 13.33 | 33.33 |
| | 25.00 | 66.67 | |
| | 60.00 | 40.00 | |
| 3 | 19 | 1 | 20 |
| | 31.67 | 1.67 | 33.33 |
| | 39.58 | 8.33 | |
| | 95.00 | 5.00 | |
| Total | 48 | 12 | 60 |
| | 80.00 | 20.00 | |

### Tests

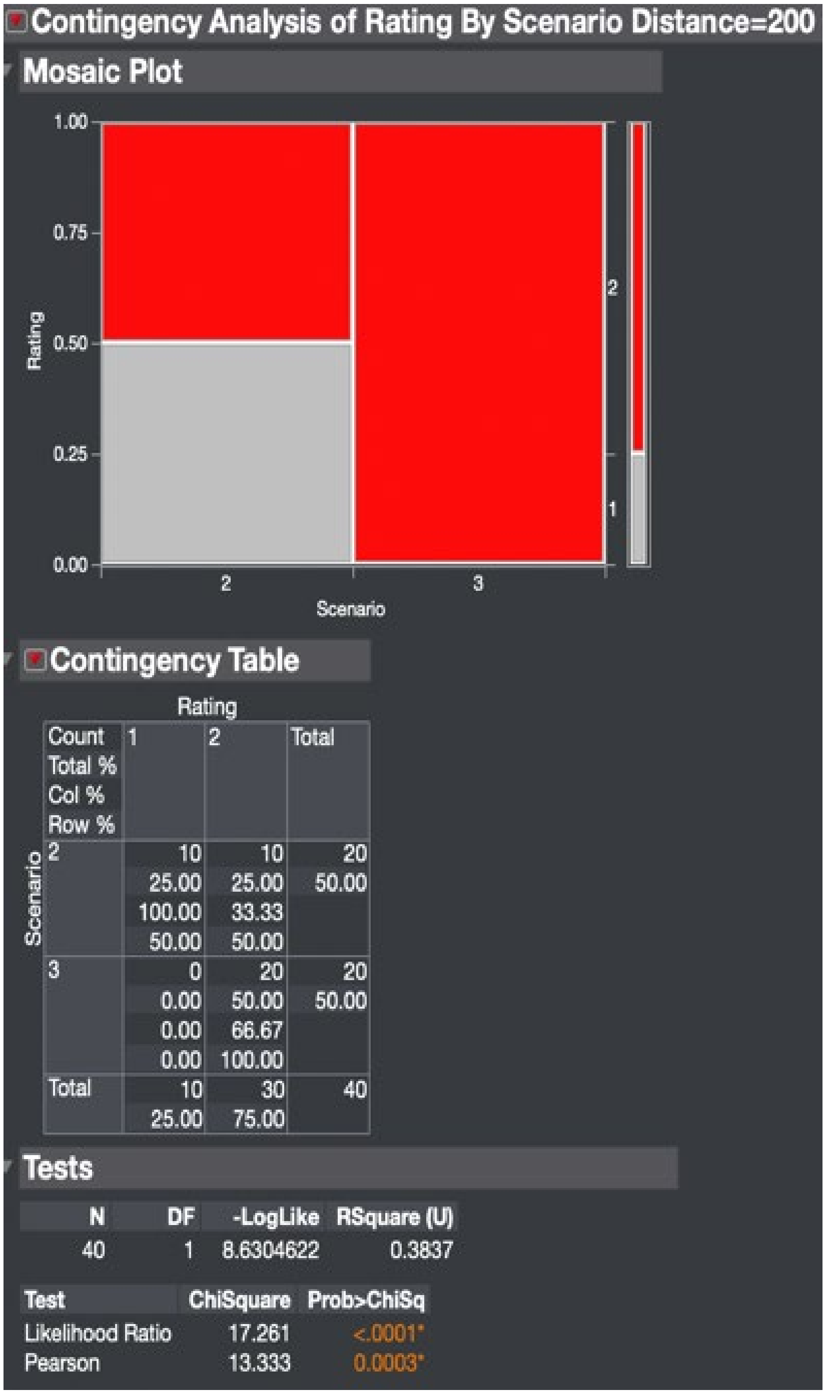
| N | DF | -LogLike | RSquare (U) |
|---|---|---|---|
| 60 | 2 | 4.1394254 | 0.1379 |

| Test | ChiSquare | Prob>ChiSq |
|---|---|---|
| Likelihood Ratio | 8.279 | 0.0159* |
| Pearson | 8.125 | 0.0172* |

Warning: 20% of cells have expected count less than 5, ChiSquare suspect.

Participants identified virtual objects visible (grey) and unidentifiable (red)

Figure 11. Contingency analysis of rating by scenario and distance, 50 m




| Count / Total % / Col % / Row % | 1 | 2 | Total |
|---|---|---|---|
| 2 | 10 | 10 | 20 |
| | 25.00 | 25.00 | 50.00 |
| | 100.00 | 33.33 | |
| | 50.00 | 50.00 | |
| 3 | 0 | 20 | 20 |
| | 0.00 | 50.00 | 50.00 |
| | 0.00 | 66.67 | |
| | 0.00 | 100.00 | |
| Total | 10 | 30 | 40 |
| | 25.00 | 75.00 | |

| N | DF | -LogLike | RSquare (U) |
|---|---|---|---|
| 40 | 1 | 8.6304622 | 0.3837 |

| Test | ChiSquare | Prob>ChiSq |
|---|---|---|
| Likelihood Ratio | 17.261 | <.0001* |
| Pearson | 13.333 | 0.0003* |

Participants identified virtual objects visible (grey) and unidentifiable (red)

Figure 12. Contingency analysis of rating by scenario and distance, 200 m

## E. RESEARCH QUESTION 2

The hypothesis examines the role animated movement has in the subject's ability to identify a virtual object. This is due to the fact most targets engaged in combat are not static. Furthermore, it provides insight into the level and type of detail developers need to provide to aide in target identification outdoors.

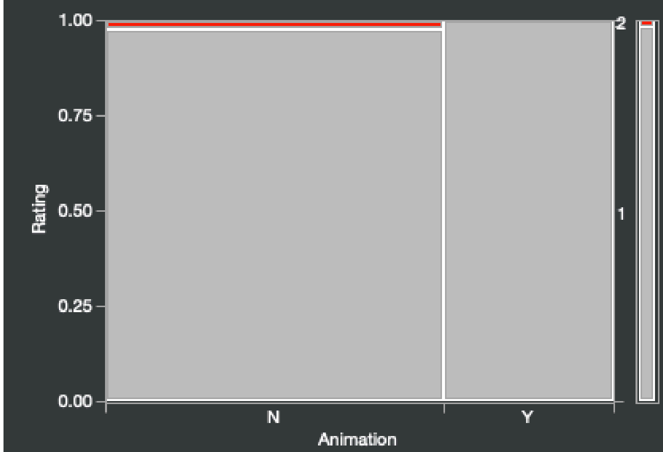
> ***Hypothesis 2 (HA2): Across subjects, animation of 3D entities at distances up to 200 m within the parameters defined, on average, will improve identification when compared to similar objects at ranges, 90% of the time, $\mu > .90$.***

The analysis indicates that animation did not aide users in a statistically significant manner (Chi- square (1) = .819, $p < 0.3654$ (Figure 13). We retain the null hypothesis as mean < .90. Only 2.5% more users could identify the VE when it was animated versus when it was not animated (Figure 14). To generate the Chi- square analysis, all scores three and below were assigned to one (identifiable object type), and all scores four or more were assigned a two (unidentifiable object type).

The minimal effects of animation are further evident when reviewing the grouped mean for both animated VEs (n = 40, mean = 1.4) versus the non-animated VE (n = 20, mean = 1.5) (Figure 14). This indicates an improved score of only 0.1 in the ability to identify the VE when 50 m from the observer (subject) using the MR device.

## Contingency Analysis of Rating By Animation Distance=50

### Mosaic Plot




### Contingency Table

| Animation | Count / Total % / Col % / Row % | Rating 1 | Rating 2 | Total |
|---|---|---|---|---|
| N | Count | 39 | 1 | 40 |
| | Total % | 65.00 | 1.67 | 66.67 |
| | Col % | 66.10 | 100.00 | |
| | Row % | 97.50 | 2.50 | |
| Y | Count | 20 | 0 | 20 |
| | Total % | 33.33 | 0.00 | 33.33 |
| | Col % | 33.90 | 0.00 | |
| | Row % | 100.00 | 0.00 | |
| Total | Count | 59 | 1 | 60 |
| | Total % | 98.33 | 1.67 | |

### Tests

| N | DF | -LogLike | RSquare (U) |
|---|---|---|---|
| 60 | 1 | 0.40969058 | 0.0806 |

| Test | ChiSquare | Prob>ChiSq |
|---|---|---|
| Likelihood Ratio | 0.819 | 0.3654 |
| Pearson | 0.508 | 0.4758 |

| Fisher's Exact Test | Prob | Alternative Hypothesis |
|---|---|---|
| Left | 0.6667 | Prob(Rating=2) is greater for Animation=N than Y |
| Right | 1.0000 | Prob(Rating=2) is greater for Animation=Y than N |
| 2-Tail | 1.0000 | Prob(Rating=2) is different across Animation |

Participants identified virtual objects visible (grey) and unidentifiable (red)

Figure 13. Chi- square analysis of animation by distance, 50 m

| Avg[50 person 1,50 Person 2] | | 50 Person 3 | |
|---|---|---|---|
| Mean | Std Err | Mean | Std Err |
| 1.4 | 0.093189 | 1.5 | 0.1538967528128 |

Figure 14. Grouped mean analysis, animated vs. non-animated

## F. EXPLORATORY QUESTION: TO WHAT EXTENT CAN ADJUSTED LIGHT LEVELS OF 3D ENTITIES SUPPORT IDENTIFICATION AT RANGES OF 20–300 M?

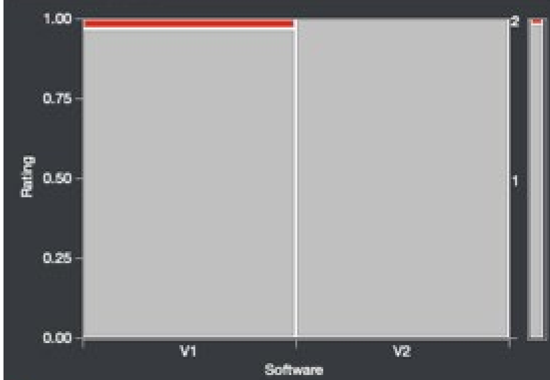
As the observational study began, a delayed software update prototype became available, and was available shortly after commencing observational test. After the first 10 test subjects, the updated software was employed for observational testing. This software allowed for the light levels and angle of lighting for all virtual objects and people to be updated simultaneously by the researcher. The software did not allow for individual entities to be updated. The Mosaic Plot and Contingency Table indicate the percentage of subjects who rated the VEs as identifiable (1) or unidentifiable (2). A Chi- square test was conducted to determine if there was an improvement in subjects' ability to identify VEs at 50, 100, and 200 m.

### 1. Software Performance at 50 m

The analysis indicates that software did not aid users in a statistically significant manner at 50 m Chi- square (1) = 1.403, p = 0.2362 (Figure 15). About 98% of the subjects were able to identify the type of VE at 50 m regardless of the type of software employed. All of the subjects identified the VEs when Software Version 2 was employed, which was a 3.33% improvement over Software Version 1.

**Contingency Analysis of Rating By Software Distance=50**

**Mosaic Plot**




**Contingency Table**

| Count / Total % / Col % / Row % | Rating: 1 | 2 | Total |
|---|---|---|---|
| Software: V1 | 29 | 1 | 30 |
| | 48.33 | 1.67 | 50.00 |
| | 49.15 | 100.00 | |
| | 96.67 | 3.33 | |
| V2 | 30 | 0 | 30 |
| | 50.00 | 0.00 | 50.00 |
| | 50.85 | 0.00 | |
| | 100.00 | 0.00 | |
| Total | 59 | 1 | 60 |
| | 98.33 | 1.67 | |

**Tests**

| N | DF | -LogLike | RSquare (U) |
|---|---|---|---|
| 60 | 1 | 0.70162216 | 0.1380 |

| Test | ChiSquare | Prob>ChiSq |
|---|---|---|
| Likelihood Ratio | 1.403 | 0.2362 |
| Pearson | 1.017 | 0.3132 |

| Fisher's Exact Test | Prob | Alternative Hypothesis |
|---|---|---|
| Left | 0.5000 | Prob(Rating=2) is greater for Software=V1 than V2 |
| Right | 1.0000 | Prob(Rating=2) is greater for Software=V2 than V1 |
| 2-Tail | 1.0000 | Prob(Rating=2) is different across Software |

Participants identified virtual objects visible (grey) and unidentifiable (red)

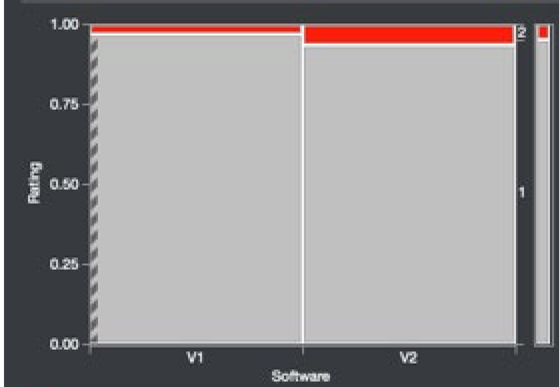
Figure 15. Software mosaic plot, contingency table, Chi- square test, 50 m

### 2. Software Performance at 100 m

Feedback from the subjects when viewing the at 100 m was nearly the same as when viewing the VEs at 50 m, but software version 2 performed 6.67% worse than at 50 m. The overall ratings slightly decreased, dropping from 98.33% of all subjects who were able to identify the VE to 95%, regardless of software type (Figure 16). When comparing the two software types, software version 1 outperformed software version 2 the Chi- square (1) = 0.357, p = 0.5500 (Figure 11) were statistically insignificant.

Contingency Analysis of Rating By Software Distance=100

Mosaic Plot




Contingency Table

| Count / Total % / Col % / Row % | | Rating 1 | 2 | Total |
|---|---|---|---|---|
| Software | V1 | 29 | 1 | 30 |
| | | 48.33 | 1.67 | 50.00 |
| | | 50.88 | 33.33 | |
| | | 96.67 | 3.33 | |
| | V2 | 28 | 2 | 30 |
| | | 46.67 | 3.33 | 50.00 |
| | | 49.12 | 66.67 | |
| | | 93.33 | 6.67 | |
| | Total | 57 | 3 | 60 |
| | | 95.00 | 5.00 | |

Tests

| N | DF | -LogLike | RSquare (U) |
|---|---|---|---|
| 60 | 1 | 0.17867142 | 0.0150 |

| Test | ChiSquare | Prob>ChiSq |
|---|---|---|
| Likelihood Ratio | 0.357 | 0.5500 |
| Pearson | 0.351 | 0.5536 |

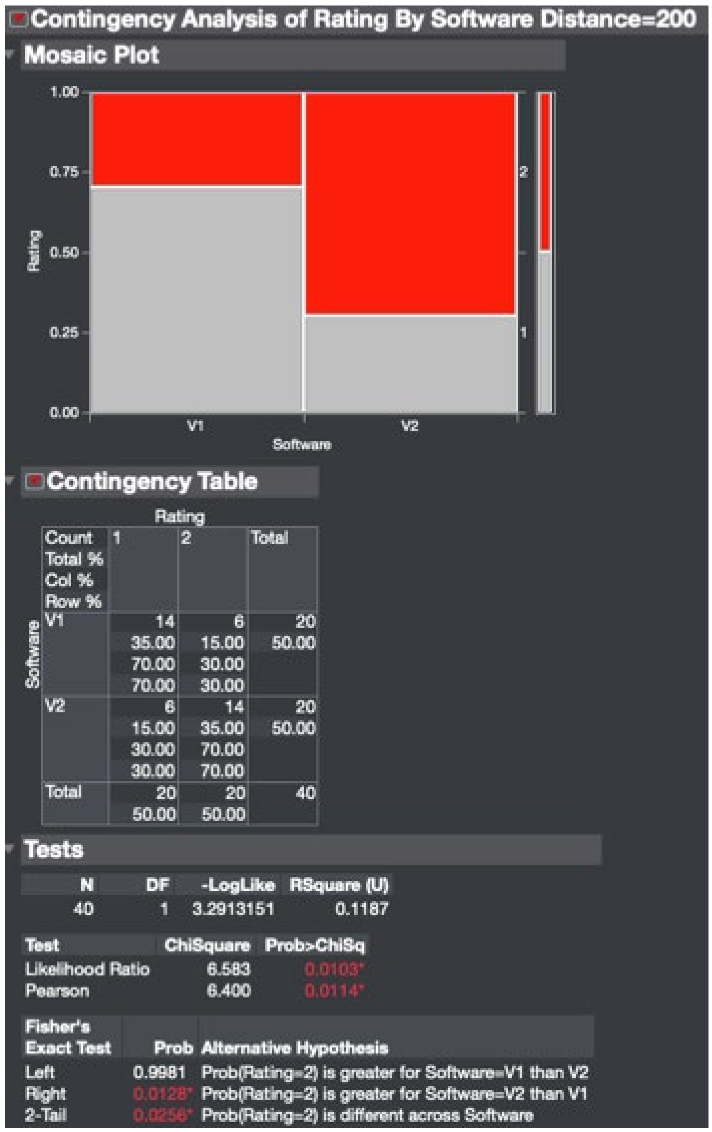
| Fisher's Exact Test | Prob | Alternative Hypothesis |
|---|---|---|
| Left | 0.8814 | Prob(Rating=2) is greater for Software=V1 than V2 |
| Right | 0.5000 | Prob(Rating=2) is greater for Software=V2 than V1 |
| 2-Tail | 1.0000 | Prob(Rating=2) is different across Software |

Participants identified virtual objects visible (grey) and unidentifiable (red)

Figure 16. Software mosaic plot, contingency table, Chi- square test 100 m

### 3. Software Performance at 200 m

The difference in software performance at 200 m was statistically significant, with a Chi- square (1) = 6.583, p = 0.0103 (Figure 17). 30% of the subjects using version 2 of the software were able to identify the type of object versus 70% of the subjects who were able to identify the type of object using version 1. It should be noted that the majority of subjects, 50%, regardless of the software version, were able to identify the VEs at 200 m.




Participants identified virtual objects visible (grey) and unidentifiable (red)

Figure 17. Software mosaic, contingency table, Chi- square test, 200 m

## G. DEMOGRAPHIC AND POST-TASK SURVEY

We explored the relationship between survey feedback and the subjects' observational test results. First, we will examine a potential correlation between user enemy identification training and feedback. Next, post-task survey results regarding MR application in training will be discussed. The post-task results specifically focus on feedback regarding strenuous training use and factors which complicated identification of VEs.

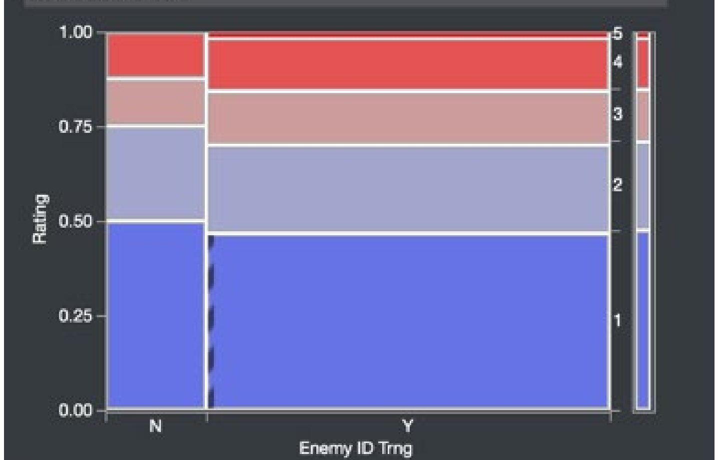
The Post-task survey solicited subjects' feedback to identify challenges and recommendations. The questions specifically asked about characteristics of the VEs which were used for identification. It also explored the ability to identify VEs in stressful, physically demanding situations. The researchers solicited feedback on environmental factors such as bright light and background clutter. Last, the survey asked if MR can be used to improve training and if there were any health issues such as eye strain.

After examining the post-task survey, we noticed that subjects trained in identifying enemy vehicles or personnel appeared to provide a lower response rating; reasons for this are discussed in the Conclusions chapter. In order to gain greater insight into this observation, we conducted a Chi- square analysis. This analysis differed from previous analysis in this study as we kept the original Likert ratings (1-5), with 1 being "clearly visible," and 5 representing "not visible." The original ratings were maintained as it provided nuanced insight when the Chi- square analysis was run. Approximately 20% of the subjects have not received vehicle or enemy recognition training. When comparing the enemy identification training effect on user feedback, Chi- square (4) = 1.064, p = 0.9000 (Figure 18) indicate results are statistically insignificant. The antidotal feedback suggest that personnel trained in enemy identification are more discerning in rating the quality of the VEs which are presented.

The most interesting and ambiguous, Likert rating is "3." It is defined as "visible, difficult to determine object." The rating was awarded by 14% of those who received the identification training, and 12.5% of the personnel who had not received the training. When exploring the poorer ratings, contingency table shows that ratings 4 (visible, could not determine object type) and 5 (not visible) were awarded by 15% of subjects who received enemy identification training, whereas 12.5% of subjects who did not receive the training awarded the ratings. When examining the best ratings (1 = clearly visible, 2 = visible under most conditions), a lower percentage of trained subjects provided a 1 (46.8%) or 2 (23.4%) versus untrained subjects who provided a 1 (50%) or 2 (25%).

**Contingency Analysis of Rating By Enemy ID Trng**

**Mosaic Plot**




**Contingency Table**

| Enemy ID Trng | Count / Total % / Col % / Row % | Rating 1 | 2 | 3 | 4 | 5 | Total |
|---|---|---|---|---|---|---|---|
| N | Count | 16 | 8 | 4 | 4 | 0 | 32 |
| | Total % | 10.00 | 5.00 | 2.50 | 2.50 | 0.00 | 20.00 |
| | Col % | 21.05 | 21.05 | 18.18 | 18.18 | 0.00 | |
| | Row % | 50.00 | 25.00 | 12.50 | 12.50 | 0.00 | |
| Y | Count | 60 | 30 | 18 | 18 | 2 | 128 |
| | Total % | 37.50 | 18.75 | 11.25 | 11.25 | 1.25 | 80.00 |
| | Col % | 78.95 | 78.95 | 81.82 | 81.82 | 100.00 | |
| | Row % | 46.88 | 23.44 | 14.06 | 14.06 | 1.56 | |
| Total | Count | 76 | 38 | 22 | 22 | 2 | 160 |
| | Total % | 47.50 | 23.75 | 13.75 | 13.75 | 1.25 | |

**Tests**

| N | DF | -LogLike | RSquare (U) |
|---|---|---|---|
| 160 | 4 | 0.53179713 | 0.0026 |

| Test | ChiSquare | Prob>ChiSq |
|---|---|---|
| Likelihood Ratio | 1.064 | 0.9000 |
| Pearson | 0.670 | 0.9550 |

Warning: 20% of cells have expected count less than 5, ChiSquare suspect.

Mosaic Plot Ratings, Blue = 1, Light Blue = 2, Light Red = 3, Red = 4, and Dark Red = 5

Figure 18. Subject rating by previous enemy identification training

In order to attain user feedback about the technology's potential, it was important to gain their insight regarding MR's application during intense training. This is important to ask as most subjects/users are unable to stand still in an optimal position to observe a VE. The question was phrased as follows:

"How well do you think you will be able to recognize the image during a physically demanding training event?"

The general feedback regarding the technology's potential in an actual training environment shows that future users are receptive to the technology (Table 2). The two respondents who selected "poor" serve in the sustainment and maneuver/combat arms fields. The respondent who chose "very well" serves in the sustainment field.

Table 2. Post-task survey, MR potential in demanding training environment

| Very Poorly | Poor | Average | Well | Very Well |
|---|---|---|---|---|
| 0 | 2 | 6 | 10 | 1 |

In order to gain insight into environmental factors, subjects were asked about common factors which are encountered when MR is used outdoors. The most common complicating factor was bright light, followed by camouflage/background clutter, and then shadows. Bright light tends to dissipate the strength of the image the user is viewing (Table 3). Camouflage/Clutter tends to allow the VE to blend into background objects, which may not be a negative concern since the object would blend in the background in reality. Shadows can sometimes obscure the VE if it is a darker image.

Table 3. Post-task survey, complicating environmental factors

| Bright Light | Camo/Clutter | Shadows |
|---|---|---|
| 10 | 8 | 2 |

# V. CONCLUSIONS

The primary focus of the thesis was to explore technologies that seek to overcome two major challenges for practical outdoor application of MR. Specifically, the thesis focused on inconsistent anchoring and light washout of virtual objects beyond 20 m. Employment of GPS was intended to address the inability to consistently anchor a virtual object at distant ranges beyond 20 m. The use of a visor, sun shader, and customized software was instituted to counter the effects of bright sun light/high lux levels. Researchers also explored the effects of animation in users' ability to identify objects in the hope it may alleviate challenges presented by high lux levels.

The researchers chose to integrate GPS to aid in positioning of VEs as the creation of an outdoor spatial map can be challenging because the HoloLens II requires an optimized lux level of 500–1000 lux (Brown et al., 2019). When light levels exceed 1000 lux, they can prevent the camera from detecting the 3D surfaces captured during the spatial mapping of the environment. Furthermore, building a spatial map of an outdoor training area, which can cover the area of two football fields, can require anywhere from 10–30 minutes. The research only applied GPS onto a pre-loaded 2D map and did not reconcile this with a spatial map.

High lux levels were initially addressed through the employment of a visor and sun shades placed over the HoloLens II field of view. Shortly after the observational study commenced, software became available to adjust the brightness and angle of light on each VE. We therefore explored the effect of this software update on participants' virtual object visibility ratings.

During development of the IVAS SiVT capability, animation was considered as an aid to assist the trainee in acquiring the target outdoors as distant ranges complicate target identification. It was believed that an animated muzzle flash or head presentation above actual cover, such as a wall, may suffice as a quality target for trainees at distant ranges. Consequently, researchers sought to explore if animation may aide in virtual target identification outdoors.

The outdoor environment, NPS, chosen for the research was diverse. It included forested and urban terrain, within 200–300 m of the ocean and fresh water streams. This environment had frequently shifting lux levels due to the capricious California Coastal Fog. Furthermore, the research took place from 0900 (09:00 a.m.)–1630 (4:30 p.m.). One scenario was observed from the 4th floor of a building, another was placed along an abandoned road, with limited obstructions to the field of view, and another in a lightly forested park. Consequently, challenges such as morning dew, strong shade, foot/vehicular traffic, buildings, communication antennas, and elevation introduced real-world challenges into the research environment.

## A. SUMMARY OF RESULTS

### 1. GPS Contribution

The primary goal was to explore GPS ability to accurately anchor the VE with a secondary goal of aiding the trainer in building the scenario. During early pilot testing of the software, the GPS capability was not functional. This lack of functionality resulted in the VEs placement being 180–220 degrees in the wrong direction in relation to the observer and 200–400 m further in range from the observer. The VEs could also appear above or below the researcher's elevation. Furthermore, the VEs placement when the scenario was activated was inconsistent. This resulted in the researcher spending approximately 15 minutes working to correct these deficiencies for each scenario for a total of 45 minutes. After the GPS capability was integrated into the software, the VEs were locked in range and elevation. The direction of the entities within the scenario were adjusted to ensure consistent placement. The VEs could not be individually moved. The introduction of GPS allowed the scenario to be established within 5–10 minutes.

As range increased, the consistency of VEs placement would shift both horizontally and vertically. More importantly, minor changes in elevation in the outdoor environment beyond a distance of 200 m made it impossible for the researcher to introduce VEs at 250 or 300 m despite multiple attempts. For example, a subject would have to walk 200 m to see the object 300 m away from the original observation point. The researcher's observation about horizontal anchoring of objects is validated in subjects' feedback. This issue was most evident in Scenario 2. Scenario 2 was placed on a vacant road, with no major obstacles occluding the VEs and the subject/researcher. On one side of the road was Hermann Hall, and the other side was one-story offices. This created a narrow space in which to place the VEs, which is not uncommon when training for urban warfare. When there were high lux levels, specifically between 1030 and 1530, the VEs at 100 and 200 m merged close together. This is most evident when comparing the results (Figure 11) of the three scenarios at 100 m. The results for Scenario 2 have a 90% probability of identifying compared to Scenario 1, with a probability of identification of 95%. Scenario 3 has a probability of identification of 100%. Scenario 2 had the poorest performance, which is 5% less than Scenario 1, and 10% less than Scenario 2.

### 2. Animation

Animation was examined at 50 m to gain insight into its role in aiding in target identification outdoors. There was one animated virtual human in Scenario 1, and one in Scenario 2. Scenario 3 had a fixed human. The two animated humans were civilians meant to represent a Middle Eastern or South Asian male, and the third, non-animated human was meant to represent a Soldier dressed in desert camouflage and a ballistic helmet. The results indicated that animation did not assist the subjects in identifying the virtual humans in a statistically significant manner. Regardless of whether or not animation was used, almost all participants reported the virtual humans as visible, suggesting a ceiling effect (Figure 15). It is possible that animation may be more useful at farther distances.

The animation that was analyzed was very simple, and did not actually allow the virtual human to move from one point to another. While this feature was technically possible, the amount of troubleshooting required to do this outdoors was not possible due to limited time. In Scenario 1, the civilian male was placed on a side walk, under shade, and was walking towards the subject. In Scenario 2, the civilian male was also placed on a side walk, walking towards the subject. In both scenarios, the subject viewed the civilian male within 1 m of his/her elevation. The virtual military soldier in uniform was viewed approximately 13.5 m below the subject, and 50 m away.

It is recommended that further research be conducted to explore the introduction of actual virtual object navigation and muzzle flashes seen in combat. Examples of research into outdoor animation research include point to point navigation, smoke, muzzle flash, and dust portrayals. Existing research suggests these cues may assist (El Jamiy & Marsh, 2019). Smoke, muzzle flash, and dust portrayals can aide in reducing the amount of detailed VEs required for a training scenario. It may aide in reducing on-body and local computational requirements as it may reduce the number of virtual objects to require to interact with the physical world. The angle at which the animated cues are presented must also be considered (El Jamiy & Marsh, 2019), so it is recommended that elevation is factored into future research.

### 3. Software Lighting Adjustment Capability

The ability to adjust the VEs' lighting in outdoor environments, while refining the scenario proved to be a valuable capability at the 200-meter range when comparing the performance of version 1 software against version 2. In contrast, the visibility decreased by 6% from 50 to 100 m. The effects of lighting adjustment were uniform, and did not allow for adjustment of individual VEs. The ability to adjust lighting at each range, specifically 50 and 100 m, may have led to more pronounced, improved results.

A second contextual observation is the alignment of the sun and associated rays crossed the line of sight for almost every subject, potentially resulting in a much lower average score for Scenario 2 versus Scenario 1. The VEs in Scenario 2 were positioned so that there was no shade between them and the subject. Furthermore, in Scenario 2, the sun passed directly over, from east to west, perpendicular to the subjects' line of sight, facing slightly southeast, as the observational test were conducted around the Spring Equinox. The confounding variables concerning the suns' positioning is partially true for Scenario 3, as the VE was positioned southeast of the subject, which resulted in a visibility rating similar to that of Scenario 2. While we believe the ability to adjust the software lighting levels had a negative effect on the subject's ability to clearly identify the VEs at 50 m, we think the positioning of the sun, and lack of shadows compounded the issue.

## B. LIMITATIONS

This section is intended to discuss key limitations that, if eliminated, would potentially improve the research outcomes. This section focuses on improving maps, challenges tied to positioning VEs beyond 200 m, and the ability to edit each VE.

The greatest limitation was the time required to integrate GPS into the software and conduct multiple refinements. In addition, the acquisition of a GPS signal proved challenging at times, as buildings with multiple antennas seemed to prevent acquisition of a consistent signal. Consequently, MR employment for training which requires GPS must consider electromagnetic interference. The challenges tied to GPS and supporting maps used for scenario design inhibited implementation of complex scenarios with animation. The ability to upload maps from government websites such as the National Geospatial and Intelligence Agency, whose Geospatial Repository and Data Management System includes training maps, is critical. This capability will enable the trainer to create detailed scenarios, and ensure centimeter level accuracy in VE placement.

The inability to place VEs at ranges beyond 200 m was both a software and physical terrain challenge. It is challenging to find an unobstructed field of view beyond 200 m on the ground at NPS. In order to overcome this challenge, one observation site was placed on the fourth floor of Hermann Hall. The low fidelity maps inhibited our ability to place VEs beyond the boundaries of NPS. We were unable to confidently asses and decipher critical details regarding terrain needed to accurately place the VEs. When assessing distances beyond 200 m, the trainer must understand the changes caused by elevation differences, the field of view from the intended engagement and observation locations, and the characteristics of the physical objects to properly adjust the system to ensure scenario realism. In practice, this would be incredibly difficult for trainers to do routinely, so designers should work to automate this functionality within the system. The change in terrain elevation is incredibly important because a change in elevation at 200 m or further that is more than five feet may obscure the ability for a trainee to see a VE.

The ability to edit each VE, or group several VEs for editing, while outdoors is critical. The inability to do this made refinements to the scenarios incredibly challenging and time consuming. As light levels increased, the VEs appeared closer in distance to each other as their range increased. The inability to manually move each VE to its proper location dramatically affected the user feedback in Scenario 2, as the field of view as very narrow at approximately 50 m wide.

General limitations tied to the research were primarily tied to time. Getting logistical and legal approvals to access IVAS reduced the time available for the pilot and observational testing. Originally the intent was to use an early IVAS prototype for testing. Initial familiarization with the capability, which lacked a mature user interface, and intentionally lacked labeling to aid human factor researchers, made use of the IVAS prototype challenging as engineering SMEs were required to provide familiarization. The availability of these SMEs to enable full use of the IVAS HUD was limited, especially considering each virtual coaching session took approximately one hour. Legal hurdles were an immense and timely challenge to overcome as the HoloWarrior software required approval from the IVAS project manager. The delays associated with the approval process, then working through physical security protocals prevented the time and access required to integrate the HoloWarrior software into the IVAS software.

## C. FUTURE WORK

There are many capabilities which must be matured to enable practical outdoor use of MR for robust military training outdoors. There are several challenges remaining before MR reaches its full capability. Some of these are required before first implementation, such as an enhanced editing capability while in MR, and some are not absolutely necessary, such as dynamic occlusion. There are three areas tied to the research discussed in this thesis, which would make outdoor MR application possible. First, the HoloWarrior software must support highly detailed maps to enable efficient and tactically accurate scenario development possible. Second, outdoor, entity, class, or grouped based scenario editing must be available to refine issues tied to VE drift that occurs during bright sunlight. Last, the ability to adjust lighting levels by VE, class of objects, or location must be available.

The maps available on the HoloWarrior do not support accuracy beyond 10 m. In order to overcome this, clearly visible known points were used to assist in VE placement when each scenario was designed on a laptop. The software allowed for minor adjustments in the placement of all objects simultaneously, but did not allow for adjustment of each object. Training scenario development requires many iterations and refinements, based on the unit's performance. The ability to employ detailed maps, with up to 1 cm accuracy, and to include recently generated maps are required to prevent the trainer from spending too much time editing the scenario. The ability of the software to ingest maps captured the day of training would also reduce some occlusion challenges tied to movement of large objects such as dumpsters. The GPS capability must also be integrated into a scan of the training environment to create an occlusion mesh and head tracking map. These maps can be integrated together to refine inaccuracies in the map data. The most frequent inaccuracy we dealt with is elevation data. Challenges were frequently experienced in our ability to anchor the virtual objects to the ground as the elevation data ranged from one–two meters above or below the ground. This forced us to manually adjust the elevation of each VE. It will be nearly impossible to develop a perfect outdoor MR training scenario solely on a laptop, but the integration of detailed, accurate maps is crucial to ensuring only minor refinements are required, preventing a barrier to training due to poor maps.

The HoloWarrior editing capability, which resides on the HoloLens II, must become amenable to entity or class level changes. As discussed earlier, the software only allowed for refinement to the comprehensive scenario. This meant that when environmental factors moved a VE at a specific range by 3 m, we had to move all entities simultaneously to ensure they were properly positioned. This also forced us to completely re-edit the scenarios to ensure we had space in the physical world to adjust the VEs. This limitation dramatically reduces the trainer's ability to adjust scenarios. Future software development should allow for micro-editing outdoors, while wearing the HoloLens II. The ability to move each VE in elevation or its position on the ground maximizes the available training area. This resulted in the occlusion or overlap of some VEs. We recommend this capability be explored using both an X-Box controller, and hand gestures, such as tap and hold, gaze, or the laser pointer. This editing capability will be required to ensure quick scenario refinements, even when the GPS and maps are improved.

The effects of high lux levels at ranges beyond 100 m are difficult to overcome without further improvements to the HoloWarrior software. The software must allow the trainer have the option to adjust lighting levels at a macro level, and also a micro level, similar to what was described when discussing the movement of VEs. These two light adjustments are required as the sunlight crosses the line of sight of the user leading to users perceiving the location of each VE differently. This ability to adjust both the lighting angle and the brightness level for each VE is critical to ensuring at ranges beyond 200 m. This capability should also be assessed at near ranges, as the research in this thesis suggest lighting levels had minimal impact at 50 m, and a degrading impact at 100 m.

## D. CONCLUSION

This research informs the next steps necessary for enabling outdoor employment of MR for training. MR has the capability to be an invaluable tool to enable outdoor training and understand employment techniques. Furthermore, manual adjustment of the scene and its lighting can bridge the gap until unsupervised machine learning algorithms can yield results which enable dynamic occlusion within an occlusion mesh. The results of this research suggest that both GPS employment and software-enabled lighting of VEs can improve the ability of trainees to see holographs at distant ranges outdoors. Further research and development which enables trainers to refine each object, and enables incorporation of high-fidelity terrain data can enable outdoor training using MR. Consequently, this capability can enhance realism, reduce training related cost, and most importantly, enhance warfighter lethality.

# APPENDIX. SURVEYS

## A. DEMOGRAPHIC SURVEY

**Exploring the ability to employ virtual entities outdoors at ranges beyond 20 meters**

Demographic Survey

Subject Number: _____________ Date: ______________

1. Age:

2. Gender: Male Female

3. Have you used a Virtual Reality Device? Yes No

4. Have you served or do you currently serve in the Armed Forces: Yes No

*If "No" you are complete with survey

   a. Which branch: USA USN USMC USAF USCG

   b. Years of Service: _________

   c. Highest Rank: __________

Functional Area/Specialty (circle one):
Maneuver Intelligence Fires Sustainment Communications Aviation
Military Police

5. Have you used a Mixed or Augmented Reality Device (Transparent) Yes No

   a. How often? <2 hrs/wk 2-4 hrs/wk 4-8 hrs/wk >8 hrs/wk

   b. Do you easily experience nausea, disorientation, or headaches during experiences flights, roller coaster rides, or from bright lights? Yes No

   c. Have you experienced dis-orientation or nausea when wearing a virtual reality or augmented reality headset? Yes No

6. Have you received vehicle or military equipment identification training? Yes No
   *If NO, proceed to question #7.

   a. Were you tested on your equipment identification skills? Yes No

   b. When was the last time you conducted military equipment identification training?

      <2 Years Ago 2-4 Years Ago 4+ Years Ago

7. Have you served as a forward observer, JTAC, ALO, Special Operations, scout, tank gunner, sniper, geo-spatial intelligence analyst, or CAS platform pilot? Yes No

   a. When was the last time you served in that position?

      <2 Years Ago 2-4 Years Ago 4+ Years Ago

## B. POST-TASK SURVEY

**Exploring the ability to employ virtual entities outdoors at ranges beyond 20 meters**

Mixed Reality

Post-Task Survey

Subject Number: _____________ Date: ______________

1. What was the quality of the images?

| | Image Type | | | | |
|---|---|---|---|---|---|
| **Distance** | HMMWV | Large Truck | Soldier | Civilian | Building |
| 50 | | | | | |
| 100 | | | | | |
| 200 | | | | | |
| 300 | | | | | |

1 = Clearly Visible
2 = Visible, identifiable under most conditions
3 = Visible, difficult to determine object type
4 = Visible, could not determine object type
5 = Not Visible

2. What did you use to locate the virtual entity?

   Digital Textures Reflectivity Object Type

3. Using this technology, how well do you think you will be able to recognize the images during a physically demanding training event?

   Very well Well Average Poorly Very Poorly

4. In general, were the images appropriately placed in the environment? Yes No

5. Which environmental factors challenged your ability to identify the images? Circle all that apply.

   Shadows Bright Light Camouflage/Clutter None

6. Do you believe an improved version of this tool can improve training in the operation forces?
   Yes No
   Please Explain:

7. Did the AR device cause nausea, eye strain, or other discomfort? Yes No
   If YES, please explain:

# LIST OF REFERENCES


Cho, D., Ham, J., Oh, J., Park, J., Kim, S., Lee, N.-K., & Lee, B. (2017). Detection of stress levels from biosignals measured in virtual reality environments using a kernel-based extreme learning machine. *Sensors (Basel, Switzerland)*, *17*(10), 2435. https://doi.org/10.3390/s17102435

Cutting, J. E., & Vishton, P. M. (n.d.). *Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth*. 37.

Debandi, F., Iacoviello, R., Messina, A., Montagnuolo, M., Manuri, F., Sanna, A., & Zappia, D. (2018). Enhancing cultural tourism by a mixed reality application for outdoor navigation and information browsing using immersive devices. *IOP Conference Series: Materials Science and Engineering*, *364*, 012048. https://doi.org/10.1088/1757-899X/364/1/012048

Brown, D., Wen, Q., Hanson, B., Jaz, J., Miller, E., O'Reilly, L., & Paniagua, S. (2019). *HoloLens environment considerations*. Retrieved August 1, 2021, from https://docs.microsoft.com/en-us/hololens/hololens-environment-considerations

Bymer, L. (2012, August 1). *DSTS: First immersive virtual training system fielded.* Retrieved October 1, 202, from https://www.army.mil/article/84728/dsts_first_immersive_virtual_training_system_fielded#:~:text=With%20emerging%20technology%20of%20the,Soldier%20Training%20System%20this%20week.

El Jamiy, F., & Marsh, R. (2019). Survey on depth perception in head mounted displays: Distance estimation in virtual reality, augmented reality, and mixed reality. *IET Image Processing*, *13*(5), 707–712. https://doi.org/10.1049/iet-ipr.2018.5920

Fukusima, S. S., Loomis, J. M., & Da Silva, J. A. (1997). Visual perception of egocentric distance as assessed by triangulation. *Journal of Experimental Psychology: Human Perception and Performance*, *23*(1), 86–100. http://dx.doi.org/10.1037/0096-1523.23.1.86

Gallagher, M., & Ferrè, E. R. (2018). Cybersickness: A multisensory integration perspective. *Multisensory Research*, *31*(7), 645–674. https://doi.org/10.1163/22134808-20181293

Haselton, T. (2019, April 6). *How the Army plans to use Microsoft's high-tech HoloLens goggles on the battlefield*. CNBC. https://www.cnbc.com/2019/04/06/microsoft-hololens-2-army-plans-to-customize-as-ivas.html

Hughes, C. L., Fidopiastis, C., Stanney, K. M., Bailey, P. S., & Ruiz, E. (2020). The Psychometrics of cybersickness in augmented reality. *Frontiers in Virtual Reality*, *1*. https://www.frontiersin.org/article/10.3389/frvir.2020.602954

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, *3*(3), 203–220. https://doi.org/10.1207/s15327108ijap0303_3

Matsumoto, K., Muta, M., Cheng, K., & Masuko, S. (2017). Selecting moving targets in AR using head orientation. *ICAT-EGVE 2017—Posters and Demos*, 2 pages. https://doi.org/10.2312/EGVE.20171374

Nichols, S., & Patel, H. (2002). Health and safety implications of virtual reality: A review of empirical evidence. *Applied Ergonomics*, *33*(3), 251–271. https://doi.org/10.1016/S0003-6870(02)00020-0

Praschl, C., Krauss, O., & Zwettler, G. (2018). *Towards retooling the Microsoft HoloLens as outdoor AR and MR device*. 11.

Reitz, E., & Seavey, K. (2016, December 1). *Virtual Dismounted Infantry Training: Requiem for a Dream*.

*SL-18-2-Regaining-Tactical-Overmatch-The-Close-Combat-Lethality-Task-Force.pdf*. (n.d.). Retrieved September 25, 2021, from https://www.ausa.org/sites/default/files/publications/SL-18-2-Regaining-Tactical-Overmatch-The-Close-Combat-Lethality-Task-Force.pdf

Stanney, K., Lawson, B. D., Rokers, B., Dennison, M., Fidopiastis, C., Stoffregen, T., Weech, S., & Fulvio, J. M. (2020). Identifying causes of and solutions for cybersickness in immersive technology: Reformulation of a research and development agenda. *International Journal of Human–Computer Interaction*, *36*(19), 1783–1803. https://doi.org/10.1080/10447318.2020.1828535

Wang, W., Wu, X., He, A., & Chen, Z. (2019). Modelling and visualizing holographic 3D geographical scenes with timely data based on the HoloLens. *ISPRS International Journal of Geo-Information*, *8*(12), 539. https://doi.org/10.3390/ijgi8120539

Zeller, M., Arya, H., Tieto, V., Ferrone, H., Coulter, D. (2018). *Spatial mapping mixed reality*. Retrieved August 1, 2021, from https://docs.microsoft.com/en-us/windows/mixed-reality/design/spatial-mapping

# INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California