2020-06

USING AUGMENTED REALITY TO ENHANCE SITUATIONAL AWARENESS FOR AIRCRAFT TOWING

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http://hdl.handle.net/10945/65517

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

USING AUGMENTED REALITY TO ENHANCE SITUATIONAL AWARENESS FOR AIRCRAFT TOWING

by

Colton S. Fetterolf

June 2020

Thesis Advisor:	Quinn. Kennedy
Co-Advisor:	Perry L. McDowell

Research for this thesis was performed at the MOVES Institute.

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

1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2020	**3. REPORT TYPE AND DATES COVERED** Master's thesis

4. TITLE AND SUBTITLE USING AUGMENTED REALITY TO ENHANCE SITUATIONAL AWARENESS FOR AIRCRAFT TOWING	**5. FUNDING NUMBERS** NPS-20-233
6. AUTHOR(S) Colton S. Fetterolf	
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) Commander of Naval Air Forces, San Diego, CA 92135; Office of Naval Research Code 34, Arlington, VA 22217; Commander of Naval Air Forces Force Readiness Analytics Group, San Diego, CA 92135	**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)

According to FY2014–FY2019 USN Web-Enabled Safety System data, 35 mishaps and 24 hazardous incidents (i.e., HAZREPS) occurred because of aircraft towing collisions, resulting in a monetary impact in excess of $14.4 million. This thesis explored the concept of using augmented reality (AR) as an operational tool to aid a tow crew director during the towing process. Feasibility testing of the AR system was conducted by creating a Unity-based, virtual reality (VR) program called aircraft towing enhanced with AR (ATEAR). ATEAR simulated an AR system in VR, and was designed to enhance a tow crew director’s understanding of an aircraft’s edges relative to surrounding objects on a flight line during the towing process. The 2020 COVID-19 outbreak prevented the research team from conducting the experiment using qualified aircraft maintenance personnel. However, pilot testing results from Naval Postgraduate School students indicated that the AR system could increase a tow crew director’s situational awareness and, in turn, decrease the likelihood of future towing incidents. This thesis showcases the proof of concept gleaned from pilot testing and describes a method of implementing such a device in the real world for use by aircraft tow crews in the Navy and Marine Corps.

14. SUBJECT TERMS naval aviation, mishap, aircraft collision, Marine Corps aviation, towing, AR, virtual reality, VR, aircraft towing enhanced with AR, ATEAR	**15. NUMBER OF PAGES** 213
	16. PRICE CODE

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

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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USING AUGMENTED REALITY TO ENHANCE SITUATIONAL AWARENESS FOR AIRCRAFT TOWING

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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
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ABSTRACT

According to FY2014–FY2019 USN Web-Enabled Safety System data, 35 mishaps and 24 hazardous incidents (i.e., HAZREPS) occurred because of aircraft towing collisions, resulting in a monetary impact in excess of $14.4 million. This thesis explored the concept of using augmented reality (AR) as an operational tool to aid a tow crew director during the towing process. Feasibility testing of the AR system was conducted by creating a Unity-based, virtual reality (VR) program called aircraft towing enhanced with AR (ATEAR). ATEAR simulated an AR system in VR, and was designed to enhance a tow crew director's understanding of an aircraft's edges relative to surrounding objects on a flight line during the towing process. The 2020 COVID-19 outbreak prevented the research team from conducting the experiment using qualified aircraft maintenance personnel. However, pilot testing results from Naval Postgraduate School students indicated that the AR system could increase a tow crew director's situational awareness and, in turn, decrease the likelihood of future towing incidents. This thesis showcases the proof of concept gleaned from pilot testing and describes a method of implementing such a device in the real world for use by aircraft tow crews in the Navy and Marine Corps.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACR	ambient contrast ratio
AGM	aircraft ground mishap
AIMD	Aircraft Intermediate Maintenance Department
AMB	aircraft mishap board
AMMRL	aircraft maintenance material readiness list
AMO	assistant aircraft maintenance officer
AMTRP	aviation maintenance training and readiness program
AR	augmented reality
ASM	advanced skills management
ATEAR	aircraft towing enhance with augmented reality
BA	billet authorized
CADD	computer-aided design and drafting
CARMA	collaborative augmented reality maintenance assistant
CAVE	cave automatic virtual environment
CGI	computer-generated imagery
CNA	Center for Naval Analyses
CNAF	Commander of Naval Air Forces
COB	currently on board
COTS	commercial off-the-shelf
DoD	Department of Defense
EABO	expeditionary advanced based operations
EEG	electroencephalography
EMCON	emission control
FM	flight mishap
FOV	field of view
FRM	flight related mishap
GSE	ground support equipment
HDD	heads-down display
HID	holographic imageguide display
HMD	head-mounted display

HPT&E	human performance, training, and education
HUD	heads-up display
IETM	interactive electronic technical manual
IMRL	individual material readiness list
IRB	institutional review board
IST	Aviation Maintenance In-Service Training Program
LiDAR	light detection and ranging
LOS	life of service
MAF	maintenance action form
MALS	Marine Aviation Logistics Squadron
MCAS	Marine Corps air station
MIS	management information system
MOS	military occupational specialty
MOVES	modeling, virtual environments, and simulations
NAE	naval aviation enterprise
NAS	naval air station
NAVAIR	Naval Air Systems Command
NAVEDTRA	Naval Education and Training Command
NAVSAFCEN	Naval Safety Center
NAWCAD	Naval Air Warfare Center Aircraft Division
NAWCTSD	Naval Air Warfare Center Training Division
NCO	Non-commissioned Officer
NPS	Naval Postgraduate School
NRP	naval research program
ONR	Office of Naval Research
PQS	personnel qualification standards
QPT	qualified and proficient technician
RBA	ready basic aircraft
SE	support equipment
SS	simulator sickness
SME	subject matter expert
SNCO	Staff Non-commissioned Officer

SSQ	simulator sickness questionnaire
TMT	trail making test
T/M/S	Type/Model/Series
USMC	United States Marine Corps
USN	United States Navy
VAC	vergence accommodation conflict
VE	virtual environment
VR	virtual reality
WESS	web-enabled safety system

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ACKNOWLEDGMENTS

First and foremost, I would like to thank my wife, Taylor Fetterolf, for seeing me through the completion of my master’s degree. Without her patience and support, I would have been unable to devote the necessary time needed to complete my studies and research. I would also like to thank Dr. Quinn Kennedy, Mr. Perry McDowell, and Mr. Clay Greunke for their unwavering support and guidance through this process. Without their acumen and knowledge, this thesis would not have been possible. Their support on this project made a substantial impact on my professional development and forever changed my approach to academia. Additionally, I would like to thank the Naval Postgraduate School Modeling, Virtual Environments, and Simulations (MOVES) FutureTech Team (Erik Johnson, Eric Heine, Michael Guerrero, and Ryan Lee) for their guidance, support, and development of the computer program used for this thesis. Without their assistance, this thesis would not have been possible. Finally, I would like the thank the faculty at NPS who are truly dedicated to the student body and the quality of the education. Their tailored guidance and assistance made this thesis possible.

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I. INTRODUCTION

A. RESEARCH PROBLEM AND MOTIVATION

Since 2014, naval aviation has experienced a constant rise in aircraft ground mishaps (AGMs); mishaps that do not occur airborne and generally involve maintenance personnel. From FY2014-FY2019, the United States Navy (USN) and United States Marine Corps (USMC) experienced 35 mishaps and 24 hazardous incidents, or HAZREPs, because of aircraft towing collisions. Each incident was unintentional and completely avoidable, yet these incidents cost the USN and USMC $14.4 million over the 5-year period. Several studies by independent agencies point to inexperienced maintainers coupled with lack of supervision as a primary cause for AGMs as a whole (Glueck, 2017; *Department of Defense Aviation,* 2018; Nguyen, 2018). A key observation is that those in both worker roles and in supervisory roles failed to have a heightened sense of what was going on throughout daily operations (Copp, 2018a).

Even though lack of experience may be a plausible cause for these towing mishaps, this thesis aims to view the problem from a different angle. A flight line is a very dynamic, fast-paced environment. A probable cause, specifically for towing mishaps, is the visibility of flight control surfaces both during day and night operations. The standard paint scheme of all USN aircraft is a mixture of light and dark gray, which is difficult to see in not only dark environments but also extremely bright environments. The standard, light gray color of concrete also forces many segments of the aircraft to blend in with the ground. Outfitting at least one member of an aircraft tow crew with an augmented reality (AR) system that provides additional information about the aircraft position relative to objects around it, may be an effective way of increasing situational awareness to the tow crew; consequently, reducing the number of aircraft collisions during towing operations.

It is possible to use virtual reality (VR) as a platform to design and test various AR systems without incurring unnecessary costs (Geoghegan, 2015). VR provides a controlled environment to test the AR system and enables the ability to run numerous tests to determine the effectiveness of an AR system prior to physically producing a real product.

This environment also provides a method of creating a near-perfect AR system that meets the demands of the maintainers who utilize the device directly. Running scenarios in a VR environment prevents putting the safety of real aircraft and maintainers at risk when trying to test the feasibility of an AR system, and it also facilitates the capture of both objective and subjective usability metrics. This allows designers to get a good idea of the efficacy of a proposed system without the cost of building it, and test AR technologies that are neither available nor cost effective. By doing this, it can drive research and development to work on specific topics that the VR simulation show have the greatest return on investment.

B. RESEARCH QUESTIONS

The work in this thesis will focus on the following research questions:

1. How can a commercial game engine be utilized to create an accurate model of an F/A-18 towing evolution?
2. How can AR be utilized to prevent aircraft collisions during towing evolutions?
3. To what extent does AR enhance situational awareness for a tow crew director?

C. HYPOTHESES

For the purpose of this thesis research, the following three null hypotheses and alternative hypotheses have been established to address research question three:

1. Hypothesis 1

- Null Hypothesis $H1_0$: There is no difference in collision detection rate between the standard view and the AR view, $d_{ps} - {}_{pAR} = 0$
- Alternative Hypothesis $H1_A$: There is a difference in collision detection rate between the standard view and the AR view, $d_{ps} - {}_{pAR} \neq 0$

2. Hypothesis 2

- Null Hypothesis $H2_0$: There is no difference in mean stopping distance between the standard view and the AR view, $\mu d = 0$
- Alternative Hypothesis $H2_A$: There is a difference in mean stopping distance between the standard view and the AR view, $\mu d \neq 0$

3. Hypothesis 3

- Null Hypothesis $H3_0$: There is no difference in confidence levels between standard view and AR view, $\mu d = 0$
- Alternative Hypothesis $H3_A$: There is a difference in confidence levels between standard view and AR view, $\mu d \neq 0$

D. RESEARCH OBJECTIVES

- Design and develop a virtual environment (VE) using a commercial game engine called Unity. Utilize Unity to accurately model a towing evolution of an F/A-18. Utilize a VR interface to allow users to interact with the VE and measure a human's ability to identify potentially hazardous aircraft movements.
- Within the VE, develop a simulated AR overlay that provides a tow crew director with information regarding the aircraft's proximity in relation to other objects in the VE. Utilize VR to simulate AR.
- Conduct a feasibility study of the effectiveness of the simulated AR system under different towing scenarios in the VE.
- Evaluate the usability of the simulated AR system and determine whether implementing such a system in the real world would effectively serve as a viable tool to enhance the situational awareness of aircraft tow crew directors and lower the likelihood of future tow-related, aircraft ground mishaps within USN and USMC aviation.

E. BENEFITS OF STUDY

The overall goal of this study is to test the effectiveness of an AR system if it were incorporated into the aircraft towing process. Adopting such a technology, if effective, may lower the risk associated with towing aircraft during daily operations across the fleet. This technology could save the USN millions of dollars and further enable the sustained material readiness of naval aircraft across the fleet; further enabling the naval aviation enterprise (NAE) to accomplish its mission of improving readiness and producing better warfighter capabilities (Commander Naval Air Forces, n.d.). Additionally, this technology may allow the USN to consider reducing the current composition of a standard tow crew from six members to three; increasing manpower and enabling continuous execution of other maintenance actions that need to be accomplished in the squadron.

F. SCOPE OF THESIS

This thesis has four distinct areas of study:

1. The first area of study is to analyze current mishap data related to aircraft towing to determine the overall effects of the problem and justify the problem statement. Additionally, the current required training, qualification, and towing processes for aircraft tow crews in naval aviation will be included in this analysis. Because USMC aviation falls under the USN, it is important to note that all information in this area of study applies to the USMC as well. Furthermore, the term “naval aviation” will be used throughout this thesis and it encompasses both USN and USMC aviation.

2. The second area of study is to explore current AR and VR technologies, analyze their pros and cons, and look at various use cases of these technologies in the industrial and military domain. Additionally, USN proof of concept initiatives within the AR/VR domain will be discussed, along with current training initiatives regarding the towing of passenger aircraft for civilian airline personnel.

3. The third area of study is the development of a VE to replicate a portion of the F/A-18 towing process using the Unity game engine and Oculus Rift VR interface. The VE will only focus on ashore operations on a standard naval flight line. Each scenario will be constructed in such a way that the user views the world from the tow crew director's point of view. The aircraft will follow a pre-determined path, in which the user will be unable to alter. Some scenarios will be pre-programmed for the aircraft under tow to collide with an object on the flight line, while others will not. Additionally, some scenarios will utilize a simulated AR display to provide the tow crew director information regarding the aircraft under tow and its relative proximity to other aircraft and objects around it. Additionally, some scenarios will enable the user to modify the speed of the aircraft movement.

4. The fourth area of study will be focused on conducting a usability study with qualified aircraft maintainers from Naval Air Station (NAS) Lemoore and USMC air station (MCAS) Miramar. The performance of each subject will be evaluated by three metrics: collision detection rate, mean stopping distance, and the subject's confidence in their ability to foresee a collision in their respective frame of view. Subjects will experience an equal number of scenes of varying difficulty through both the standard frame of view and the AR view. Data analysis from the experiment will be conducted by comparing each subject's performance between the standard point of view and the AR view.

G. THESIS STRUCTURE

- Chapter I is an introduction regarding the problem statement, objectives, and methodology of the study.

- Chapter II discusses background information regarding the impact of towing incidents on naval aviation, current tow crew composition, current tow crew training, and current towing procedures. This chapter also contains a literature review on topics and issues related to VR and AR systems. Additionally, the chapter discusses AR and VR initiatives related to aircraft maintenance and handling in both the civilian and military domains.

- Chapter III details the design and implementation of the environment utilized for the usability study. This chapter covers technical and hardware requirements, as well as the incremental process of creating the experimental test bed environment.
- Chapter IV addresses the experimental design.
- Chapter V explains the pilot testing and the results from the pilot testing of the experimental test bed.
- Chapter VI provides a conclusion, showcases the proof of concept gleaned from the study, and suggests a plausible method of implementing such a system using modern technology, which currently exists in the DoD and commercial sector.

II. BACKGROUND

A. USN AVIATION GROUND MISHAPS

1. Mishap Classifications Defined

In a general sense, a mishap is when a piece of government equipment is damaged, regardless of intent. The Department of Defense (DoD) takes each mishap and assigns it to a particular level classification based on the severity of the mishap, injuries sustained by personnel involved in the mishap, and the overall cost incurred by the government as a result of the mishap. Mishap classifications for the DoD are governed by DoD Instruction 6055.07, which defines procedures for each branch of military service with regard to mishap notification, investigation, reporting, and record keeping (Office of the Secretary of Defense [SECDEF], 2018). In addition to DoDI 6055.07, under the direction of the Chief of Naval Operations, the Naval Aviation Safety Management System (OPNAVINST3750.6S) provides additional guidance with regard to mishap definitions and reporting procedures in the USN (Office of the Chief of Naval Operations [CNO], 2014). Strictly from a monetary standpoint, the classification scale ranges from "A" through "D" based on the severity of the mishap. A Class "A" mishap is one that costs over $2,000,000 to repair and/or total loss of an asset and a Class "D" mishap is a repair that costs less than $50,000 but greater than $20,000(Chief of Naval Operations, 2014, sec. Appendix 3A-1).).

The USN further defines a naval aviation mishap as:

> A naval aviation mishap is an unplanned event or series of events, directly involving a defined naval aircraft or UAV, that results in damage to DoD property; occupational illness to DoD personnel; injury to on or off-duty DoD military personnel; injury to on-duty DoD civilian personnel; or damage to public or private property, or injury or illness to non-DoD personnel, caused by DoD activities. (Chief of Naval Operations, 2014, para. 305)

A defined naval aircraft or UAV refers to "those aircraft and UAVs of the U.S. USN, U.S. Naval Reserve, USMC, and USMC Reserve for which the naval aircraft accounting system requires accountability" (CNO, 2014, para. 302).

The DoD mishap classification construct only accounts for mishaps that result in damage that equates to $20,000 or more. In an effort to capture incidents that ultimately cost less than $20,000, the USN requires commanders to report these incidents as hazardous reports or HAZREPs. The USN defines hazard as “any real or potential condition that can cause injury, illness, or death to personnel; damage to or loss of a system, equipment or property; or damage to the environment” (CNO, 2014, para. 501). The intent of HAZREPs is to have a method of documenting undesired events that could have turned into in mishaps under slightly different circumstances. While the USN does tie a dollar amount to HAZREPs, the overwhelming majority of HAZREPs do not involve maintenance personnel, but rather naval aviators. For example, an incident where a pilot accidentally drops ordnance “danger close” to friendly forces during a training exercise would rate a HAZREP.

In addition to mishap classifications, the USN also has created subcategories to document forms of mishaps regarding how the mishap occurred. The three subcategories are flight mishap (FM), flight related mishap (FRM), and AGM (CNO, 2014). FMs are those that occur when there was intent for flight and reportable damage occurs to the aircraft. A FRM is a mishap in which there was intent for flight, the is no reportable damage to the aircraft itself, yet the mishap involves a fatality, injury, or property damage. An AGM is a mishap where there was no intent for flight, but there is reportable damage to the aircraft and/or results in death or injury of personnel. Most AGMs solely involve maintenance personnel.

2. The Impact of Towing Incidents

Since FY2014, naval aviation has been plagued by an increase in towing-related AGMs. Many of these incidents are a direct result of Marines and Sailors accidentally towing aircraft into the aircraft hangar, a parked aircraft, ground support equipment (GSE), or some other static object on the flight line. It is important to note that USMC aviation falls under the USN’s aviation program. In all instances, the USMC follows all USN protocols and procedures. A quick Google search of “USN towing mishaps” will lead to several articles noting the rise in AGMs, but this information lacks the detail necessary to truly gain an understanding of impact of towing incidents specifically. Unfortunately, AGMs are analyzed as a whole and it is impossible to break out towing incidents using data available to the public. Limiting access to AGM towing-related data makes sense from the USN's point of view because all towing-related incidents surrounding collisions should be avoidable and are not something to be proud of.

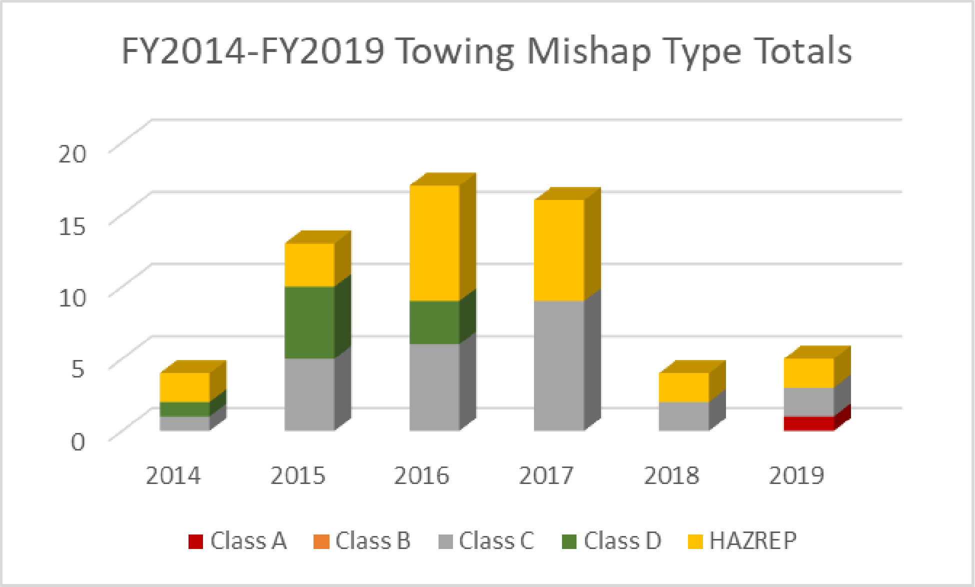
With assistance from GySgt Krystal Conklin, a senior maintenance data specialist currently serving as a data analyst with the Naval Safety Center (NAVSAFCEN), a data analysis was conducted using data pulled from the USN's web-enabled safety system (WESS). The WESS is the primary reporting system for all types of aircraft mishaps in the USN. Only personnel who require access due to their job requirements are granted access to the WESS database. The database allows a user to download an excel document by fiscal year that includes every mishap that occurred within that year. The document from the WESS includes important data like mishap type, time of day, form of mishap, type of aircraft, summary regarding the mishap, and dollar amounts associated with the mishap.

a. Number of Incidents

For information regarding the methodology used to obtain the following data, refer to Appendix B. WESS Report Data Pull Methodology. The 59 towing-related incidents found from the data pull can be further broken down into the following incident classifications (see Figure 1):

- (1) Class A mishap
- (25) Class C mishaps
- (9) Class D mishaps
- (24) HAZREPs

This data is composed of all T/M/S (Type/Model/Series) within the USN/USMC – meaning all aircraft types are included (i.e., helicopters, fighter jets, cargo support aircraft, etc.). The majority of towing incidents occurred during FY2015-FY2017, and many of these incidents were Class C mishaps and HAZREPs. When comparing FY2015-FY2017 to the remaining years in the data pull, the number of incidents for FY2015-FY2017 doubled, and in some cases tripled. This drastic increase in incidents from towing is concerning, yet an exact cause for the increase is unknown. Studies regarding mishap rates for both the USN and the USMC will be discussed further in Chapter II.A.3 of this thesis.



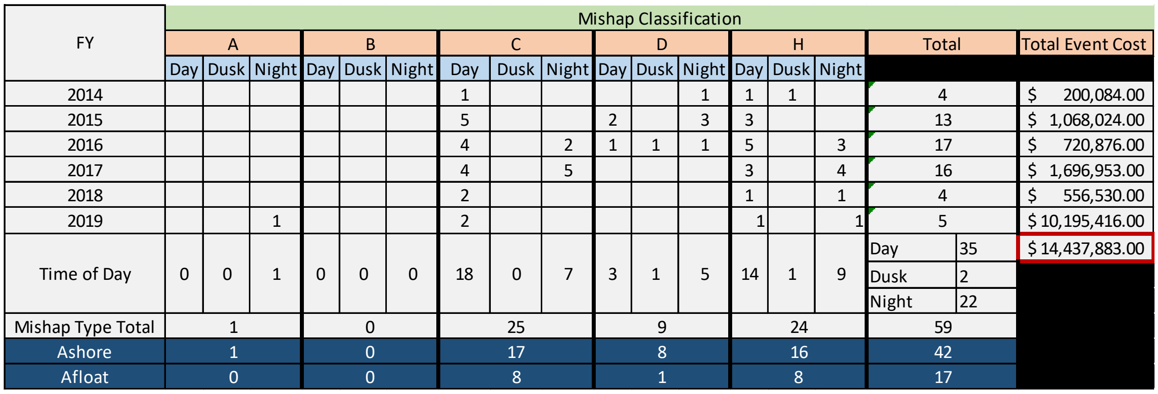
Data source: Naval Safety Center, raw unpublished data received by email, Mar. 19, 2020.

Figure 1. Number of Towing Incidents FY2014-FY2019.

For the following information, see Table 1. Of the 59 towing-related incidents, 35 occurred during the day time, 2 occurred during dusk, and 22 occurred during night operations. Dusk is defined as "when the geometric center of the Sun is 18 degrees below the horizon in the evening" (National Institute of Standards and Technology [NIST], 2019, para. 4). In layman's terms, dusk is the transition period between day and night. Towing incidents during the daytime accounted for 59.3 percent of the data, while incidents during dusk and night operations accounted for 3.4 percent and 37.3 percent, respectively. These results are surprising because operating during night time is typically inherently more difficult and risky than during the day time. Also, under normal operating conditions, the day shift maintainers typically have more supervision than a middle crew (if applicable) and night crew maintainers.

The data set was also broken down into incidents that occurred during ashore and afloat operations. 42 of the 59 incidents occurred while units were ashore (i.e., operating on a traditional flight line) and the remaining 17 incidents occurred during afloat or shipboard operations. Much like the observation that more towing incidents occur during day operations than night operations, this observation also seems to go against common intuition. With limited flight deck space and aircraft parked extremely close together (in some cases the aft of the aircraft hanging over the edge of the ship), an assumption would be that more towing incidents occur afloat. However, ashore operations account for 71.2 percent of towing incidents. Because flight operations afloat are extremely dynamic, it is plausible that afloat incidents are less likely to happen due to the strict control measures in place for ship operations that do not exist ashore.

Table 1. FY2014-FY2019 Towing Incident Overview.



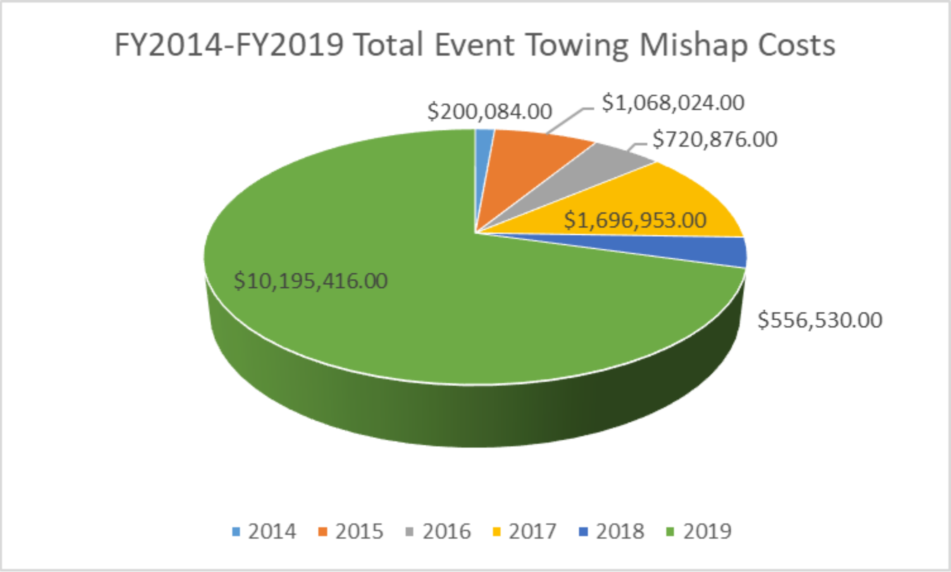
FY	Mishap Classification																
	A			B			C			D			H			Total	Total Event Cost
	Day	Dusk	Night	Day	Dusk	Night	Day	Dusk	Night	Day	Dusk	Night	Day	Dusk	Night		
2014							1					1	1	1		4	$ 200,084.00
2015							5			2		3	3			13	$ 1,068,024.00
2016							4		2	1	1	1	5		3	17	$ 720,876.00
2017							4		5				3		4	16	$ 1,696,953.00
2018							2						1		1	4	$ 556,530.00
2019			1				2						1		1	5	$ 10,195,416.00
Time of Day	0	0	1	0	0	0	18	0	7	3	1	5	14	1	9	Day 35 Dusk 2 Night 22	$ 14,437,883.00
Mishap Type Total	1			0			25			9			24			59	
Ashore	1			0			17			8			16			42	
Afloat	0			0			8			1			8			17	

Data source: Naval Safety Center, raw unpublished data received by email, Mar. 19, 2020.

b. Monetary Impact

Each time a mishap occurs, an aircraft mishap board (AMB) is appointed to investigate the incident. One of the responsibilities of the AMB is to determine the total cost of property and aircraft damage for each incident. Note that the AMB is only responsible for calculating the cost of the damage to the aircraft and/or property involved; the NAVSAFECEN will add injury costs to the total (CNO, 2014). Guidelines related to the cost assessment process for aviation mishaps can be found in paraph 316 of OPNAVINST3750.6S.

From FY2014-FY2019, towing-related incidents cost naval aviation $14,437,883 (see Table 1 and Figure 2). FY2019 yielded the second-lowest number of incidents throughout the period, yet accounted for $10.2 million of the $14.4 million total. This year's total event cost was much greater than previous years due to a class A mishap, which involved an aircraft being towed into the top of an aircraft hangar; this incident alone accounted for 98 percent of the total cost for that FY. FY2017 and FY2015 were the second and third most costly years during the time period accounting for roughly $1.7 million and $1.1 million, respectively.



Data source: Naval Safety Center, raw unpublished data received by email, Mar. 19, 2020.

Figure 2. Event Cost Totals for FY2014-FY2019.

The total cost of towing-related incidents is most likely far greater than what is documented in the WESS. OPNAVINST 3750.6S directs the AMB to exclude several things in the total cost of reported in the mishap, which results in lower cost estimates for mishaps. First, all manhours spent inspecting for damage are not included.

> Do not report man-hours spent removing or disassembling undamaged parts to gain access to areas where damage is suspected unless damage is found…Do not include those man-hours consumed setting up maintenance

> stands or other support equipment in preparation for the repair effort. (CNO, 2014, para. 316.a.4)

The manhours are documented under a different type of maintenance action form (MAF)—MAFs are essentially service tickets used to document maintenance procedures—thus these manhours are not counted towards the mishap, despite the inspection being conducted as a direct result of the mishap. Another point of concern is the lack of accounting for any form of commercial equipment or space rented to either move or repair the aircraft (CNO, 2014, para. 316.a.4). Even though renting commercial equipment is not common, this is still a cost that is incurred because of the mishap itself. Lastly, OPNAVINST3750.6S, paragraph 316.a.6 directs the AMB to not include any additional damage that may result from rescue or salvage efforts of the aircraft.

c. Intangible Effects

In addition to the monetary effects, there are two notable, intangible consequences from aircraft towing incidents: the squadron's ability to meet flight hour goals and aircraft employment for deployed operations. When addressing a squadron's ability to meet flight hour goals, it is important to understand that aircraft readiness for naval aviation has been increasingly difficult over the last 20 years due to continuous flight operations in the Middle East. When looking at the USN's Super Hornet flight hours alone, they conducted "18,000 more flight hours than they did in 2013" (Copp, 2018b, para. 3). As the USN/USMC continue to fly airframes longer than they were intended to fly, expired component contracts, engineering constraints, and components failing that weren't intended to fail are several things that increase the difficulty in maintaining the material readiness of aircraft in the fleet. Each ready basic aircraft (RBA), an aircraft that is capable of flying, is vital to meeting the daily flight schedule for each squadron. Losing an aircraft for days, and sometimes months, due to a preventable, towing incident hurts the respective squadron's ability to meet their monthly flight hour goals. With respect to a towing incident in preparation for a deployment, losing an aircraft within weeks of deploying can have dire consequences. Each aircraft is composed of thousands of components, many of which are on their own individual maintenance cycles. When an aircraft is slated for deploying with a unit, the maintenance officer of that squadron is responsible for screening the aircraft for inspections and ensuring the aircraft can fulfill the projected flight hours for the deployment without incurring any major maintenance inspections or over flying any engineering-constrained components. In communities with limited deployable aircraft, like the legacy F/A-18, this is often very difficult to do. Replacing an aircraft within two months of a scheduled deployment is a very involved and stressful process for all parties involved.

3. Studies Related to AGMs

Due to the ramifications of towing incidents and other AGMs across the fleet, a justification for the continued increase has been a point of discussion for NAE leadership over the last two to three years. Around 2016, both the USN and the USMC solicited assistance from consulting agencies to conduct independent readiness reviews of mishap data, current practices, and procedures. It is important to note that these studies are not available to the public and obtaining access to them was very difficult. The T/M/S with the highest mishap rate in the USN was the F/A-18. Consequently, the USN had the Center for Naval Analyses (CNA) conduct an analysis on increases AGMs in the F/A-18 community. The USMC had Booz Allen Hamilton conduct an all-inclusive, meaning USMC aviation as a whole and not just focused on a specific T/M/S, analysis. The general consensus from both studies was that the rise in AGMs could be attributed to inexperienced maintainers.

a. CNA Analysis and Solutions (USN)

The purpose of this study was to determine if there was a relationship between manning issues and mishap rates among the F/A-18 community in the USN (Nguyen, 2018). The mishap rate in FY2016 was double the mishap rate of FY2012. Additionally, billet gaps amongst E-7 to E-9 increased from 19 percent to 23 percent and the average time in service for E-4 to E-6 maintainers decreased about 1.5 years on average. The supervisor fit goal for the Commander of Naval Air Forces (CNAF) was 86 percent, but the highest fit from FY2011 through FY2016 was 80 percent. Supervisor fit percentage was determined by dividing the currently on board (COB) by the billet authorized (BA) and multiplying by 100 percent for each FY (Nguyen, 2018). Using historical data obtained from the WESS, N1 (USN Manpower and Personnel), and N45 (CNAF), CNA created two mishap probability curves: one at 86 percent supervisor fit and one at 75 percent supervisor fit.

They conducted a multivariable fractional polynomial logistic regression model and found a statistically significant correlation, between mishap probability and both supervisor fit percentage and E-5 life of service (LOS) time in service ratings. The model showed that the higher the supervisor fit, the lower the probability of a mishap occurring (see Figure 3).

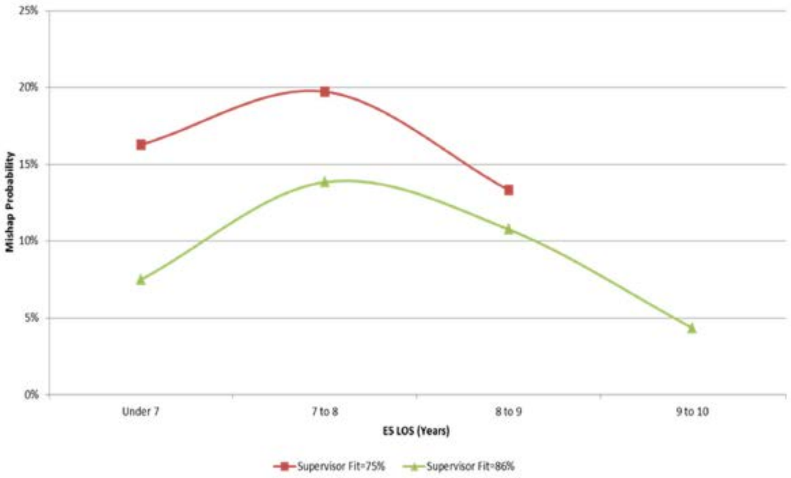


Figure 3. Mishap Probability versus Supervisor Fit (75 percent and 86 percent). Source: Nguyen (2018).

The study concluded that E-5 maintainers conducted maintenance with less experience and under less supervision in FY 2016 than FY 2011. While CNA found a strong correlation between lack of supervision and mishap rates, it is important to remember that correlation does not imply causation. The CNA report says, “we are not able to derive the impacts of the covariates, E-5 LOS and supervisor fit percentage, on the mishap probability even though we found statistically significant correlations between mishap probability and the covariates” (Nguyen, 2018, p. 13).

Even though the CNA study was very insightful, the only data they considered in their analysis was mishap rates and manpower fit/fill. Factors that contributed to the results, but were not considered were monthly flight hours conducted, operational environment (deployed/ashore/afloat/training exercise), other mishaps/incidents besides Class C mishaps, command climate, and training and education. The CNA concluded their analysis by suggesting that USN F/A-18 units maintain at least an 80 percent supervisor fit rate and at least nine years LOS for E-5 maintainers.

b. Booz Allen Hamilton (USMC)

Unlike the CNA study for the USN's F/A-18 platform, this study took a more holistic approach to the increase in AGMs across Marine aviation. They assessed the impact of seven variables in relation to AGMs: leadership, standardization, training, culture, resources, facilities, and operational tempo (Glueck, 2017). Key takeaways from each variable are as follows:

- **Leadership** – inadequate supervision on the flight line due to the overtasking of Staff Non-Commissioned Officers (SNCO).
- **Standardization** – safety and maintenance safety programs are not standardized; lack of standardized crew days, risk mitigation procedures and checklists.
- **Training** – inadequate technical expertise between the ranks of E4 and E6. Lack of maintenance safety expertise amongst squadron leadership outside of the maintenance department.
- **Culture** – expeditionary maintenance mindset resulting in finding work-arounds to accomplish the mission at all costs.
- **Resources** – inadequate GSE and individual material readiness list (IMRL), computer availability, and inadequate technical publications.
- **Facilities** - incompatible with the T/M/S of the tenant units and consistent unresolved safety-related issues.
- **Operational Tempo** - competing USMC "green side" training requirements, coupled with reaching planned flight hours only give maintenance Marines an average of 2.5-4 hours per day of aircraft touch time.

Much like the CNA study, the generalized conclusion from the Booz Allen Hamilton study was that inexperience and lack of supervision played a vital role in the increase AGMs across the USMC. In an interview with Military Times, Colonel Bianca, head of USMC aviation plans and programs, talks about how many of the AGMs in the USMC were due to unforced errors; these were instances where there should have been no added pressure to get a job done in a hasty fashion. “What we found in our independent readiness review [on] air ground mishaps was nobody had a heightened sense of what’s going on” (Copp, 2018a, para. 3).

c. Other Sources

In his 2018 address to the Tactical Air and Land Forces Subcommittee of the House Armed Services Committee, RADM Mark Leavitt, the commanding officer of the NAVSAFCEN at the time, stated the following:

> Human factors analysis studies point to breakdowns in organizational teamwork, an analysis category defined as the interaction among individuals, crews and teams involved in the preparation or execution of a task that resulted in human error or an unsafe situation. This breakdown could be related to the E-5 and E-6 inexperience issues previously noted. A similar study on USMC Class C aviation mishaps showed the same type of performance-based errors, and suggested applying the largest effort to the MV-22 and F/A-18 communities. (*Department of Defense Aviation*, 2018, p.5)

In 2013, the military felt ramifications from sequestration. “To meet the budget caps, the USN cut depot work and purchases of spare parts, which meant fewer available aircraft. It also let go of experienced mid-grade maintainers and their supervisors” (Copp, 2018b). During the same time, the USMC lost a large number of qualified maintainers. In the same *Military Times* article referenced earlier, Colonel Bianca talked about how maintenance qualifications outside of a maintainer’s military occupational specialty (MOS) were not captured properly (Copp, 2018a).

Of note, both studies cite inexperience as a contributing factor to the rise in AGMs and both studies evaluate the effects of all AGMs as a whole. Unfortunately, to date, no direct studies have been conducted towards towing incidents in particular. However, the

Booz Allen Hamilton study does draw some conclusions regarding towing incidents. From FY2012 to F2016, 20 of the 120 AGMs in the USMC were a direct result from towing. The study points out that the current composition and experience level of towing crews (discussed further in Chapter II.B) is inadequate (Glueck, 2017). Tow crews are staffed by personnel from multiple work centers. Also, there is no standardized process to force tow crew directors to consider risk mitigation measures. Furthermore, the study mentions that the highest level of supervision under the current procedure is the tow crew director; who is generally a junior Non-commissioned Officer (NCO) (i.e., E-4).

4. Summary

Towing incidents have had an impact on aircraft readiness in the NAE. The majority of towing-related incidents fall under the mishap classification of Class C or are documented as HAZREPs. From FY2014-FY2019, these incidents cost the USN and USMC over $14.4 million. The guidance in OPNAVINST3750.6S, opens the door to suspect that the true monetary cost of these incidents exceeds $14.4 million. In addition to monetary consequences, towing incidents have intangible effects on a squadron's ability to meet their monthly flight hour goals and a squadron's ability to deploy with all of their aircraft on time. The consensus across the NAE is that the rise in AGMs is a result of inexperience and lack of supervision.

B. TOW CREW COMPOSITION

An aircraft tow crew consists of six members: tow director, tow driver, brake rider, two wing walkers, and a tail walker (Department of the Navy [USN], 2017). The *Aircraft Securing and handling Procedures with Aircraft Restraining Devices and Related Components* (NAVAIR 17-1-537) directs all members of the towing crew to have familiarity with aircraft handling signals outlined in the *Aircraft Signals NATOPS Manual* (NAVAIR 00-80T-113) and be equipped with a whistle for aircraft movement (Department of the Navy [USN], 2018; USN, 2017). "All members of the movement team have a whistle, which is carried in the mouth during towing. A sharp blast on the whistle by any member of the movement team means STOP, CHOCK, and SECURE the aircraft," (USN, 2017, WP 006 00, sec. 1-8). Neither the *Naval Aviation Maintenance Program 4790.2C*

(COMNAVAIRFORINST 4790.2C) nor the NAVAIR 17-1-537 place rank restrictions on tow crew positions (Office of the Commander of Naval Air Forces [COMNAVAIRFOR], 2017). Of note, all rank suggestions provided in this thesis are common practice observed by its authors.

a. Tow Director

The tow director is ultimately responsible for the towing evolution. The tow director monitors the position of the aircraft at all times and maintains control of the movement of the aircraft. Additionally, they direct the tow driver to navigate the aircraft by use of both verbal communication and hand and arm signals outlined by NAVAIR 00-80T-113. The tow director is usually the senior ranking maintainer of the tow crew. For USN applications, the tow director generally holds the rank of E-5 or E-6. In the USMC, the tow crew director generally holds the rank of E-4. The positioning of the tow director in reference to the aircraft is noted as “TD” in Figure 4.

b. Tow Driver

The tow driver is responsible for operating the tow tractor. They follow the commands provided to them by the tow director. For USN applications, the tow driver generally holds the rank of E-5 or E-4. In the USMC, the tow driver generally holds the rank of E-4 or E-3. The positioning of the tow driver in reference to the aircraft is noted as “TTD” in Figure 4.

c. Brake Rider

The brake rider is responsible for initiating the brakes on the aircraft in the event the tow driver loses control of the aircraft. A potential instance for needing to utilize the aircraft brakes would be if the tow bar becomes damaged during the towing operation. If the braking system of the aircraft under tow is inoperable, the towing evolution will occur without a brake rider in the cockpit (USN, 2017). In the absence of a brake rider, two personnel called chock walkers, discussed in Chapter II.B.d, are added to the tow crew. These individuals shadow the wing walkers and carry wheel chocks that can be thrown down in front of the main landing gear tires to instantly stop the aircraft from further movement. For both USN and USMC applications, the brake rider generally holds the rank of E-4 or below. Additionally, chock walkers for both services generally hold the rank of E-3 or below. The positioning of the brake rider in reference to the aircraft is noted as “BR” in Figure 4.

d. Wing Walkers

There are two wing walkers present for each towing evolution. Wing walkers are stationed in parallel with the wing tips of the aircraft and are responsible for ensuring the aircraft does not collide with any object within their vicinity. For both USN and USMC applications, wing walkers generally hold the rank of E-3 or below. The positioning of the wing walkers in reference to the aircraft is noted as “WW” in Figure 4.

e. Tail Walker

The tail walker is responsible for the aft of the aircraft. In a similar role to the wing walkers, the tail walker is responsible for ensuring the aft of the aircraft does not collide with any object within their vicinity. For both USN and USMC applications, tail walkers generally hold the rank of E-3 or below. The positioning of the tail walker in reference to the aircraft is noted as “TW” in Figure 4.

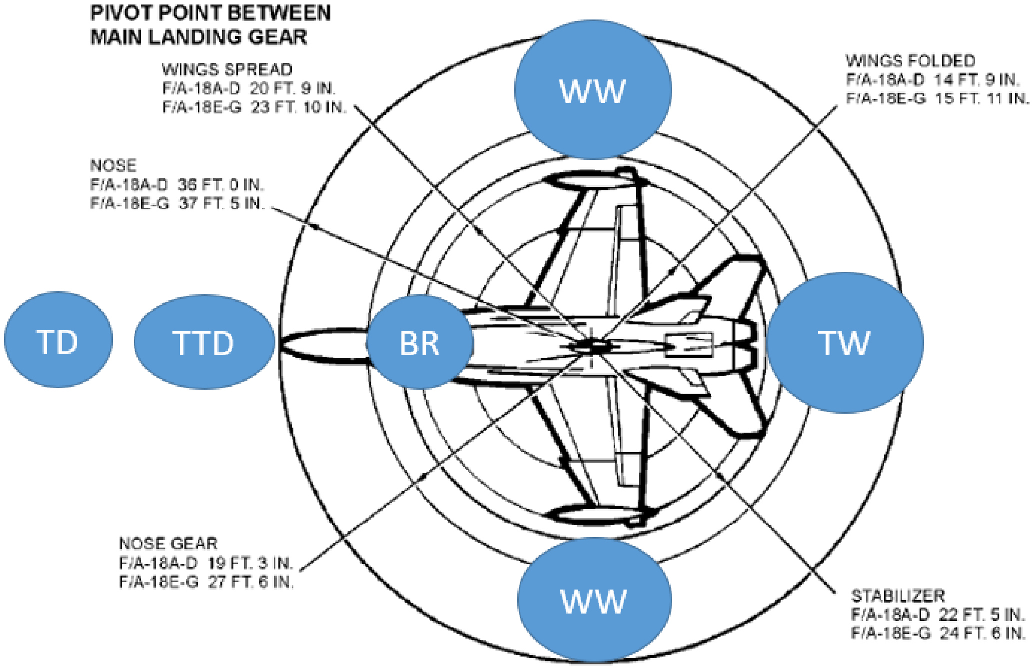


Figure 4. Aircraft Tow Crew Positioning. Adapted from USN (2017).

Wing walkers and tail walkers are generally the least experienced members of the tow crew. It is worth noting that the majority of towing-related aircraft collisions occur within the assigned sectors of wing and tail walkers. Two possible reasons why this is the case are use of junior personnel as wing and tail walkers and the location of the wing tips and horizontal stabilizers in relation to the tow crew director. The wing and tail walkers are generally the youngest, most inexperienced maintainers in the tow crew itself. They are often caught not paying attention and or not being ready to blow their whistle at any given time throughout the tow. The wing tips and the horizontal stabilizers (using a fixed-wing aircraft as an example) are the extremities of the aircraft and are a considerable distance away from the tow crew director.

C. AIRCRAFT TOWING PROCESS

The aircraft towing process is a generalized procedure that applies to all T/M/S of aircraft, and can be found in WP 006 00, section 2-4 of NAVAIR 17-1-537 (USN, 2017). The following list is an outline of the towing process:

1. Tow crew director gathers tow crew and briefs tow crew about the aircraft that needs to be towed. This brief includes where the aircraft needs to be towed, why it needs to be towed, addresses any limitations of the aircraft in relation to the towing process, and sector assignments of wing and tail walkers. Each member of the tow crew, with the exception of the brake rider and tow driver, are outfitted with a handheld, standard sports whistle. This whistle is used to alert the crew in the event the towing evolution must come to a halt for any reason.

2. The tow tractor and tow bar are connected to the aircraft.

3. Under the hand and arm signal direction of the tow crew director, the tow driver pulls the aircraft to the desired location.

4. Wing and tail walkers walk along the aircraft within ~10 feet of the aircraft and ensure the aircraft will not hit any objects, In the event anyone in the tow crew believes the aircraft is about to collide with another object, it is their responsibility to blow their whistle.

5. If a whistle is blown, the tow driver will halt movement so the tow crew director can assess the situation.

6. Once the aircraft is in the desired location, the tow tractor and tow bar are disconnected, and the aircraft is properly secured.

D. CURRENT TRAINING FOR TOW CREW PERSONNEL

Current training for tow crew personnel remains the same for both the USN and the USMC. This section will explore the training management system used for naval aviation maintenance professionals, the maintenance training program, and the current qualifications held by members of an F/A-18 tow crew.

1. Aviation Maintenance In-Service Training Program (IST)

The IST directs the implementation of all aviation maintenance-related training within the unit. The squadron's assistant aircraft maintenance officer (AMO) is responsible for the maintenance in-service training program (COMNAVAIRFOR, 2017). These responsibilities include scheduling maintainers for external training required for specific qualifications, creating and enforcing a weekly technical training plan for the squadron, as well as ensuring each maintainer is progressing through their MOS requirements. Typically, the AMO is also in charge of the GSE training and licensing program, which specifically targets the qualifications pertaining to any form of aircraft GSE. Examples of GSE include the A/S32A-45 tow tractor, NC-10C mobile electric power plant, and the 4000A engine removal/installation trailer. With regard to the aircraft towing process, the A/S32A-45 tow tractor, also referred to as a TUG. The TUG is the only piece of GSE used in the towing process that requires a license to operate.

2. Advanced Skills Management (ASM)

ASM is an "unclassified management information system (MIS) that contains job task requirements, documents completed training, qualifications, certifications, duty or billet assignments, and tracks personnel progress in completing [qualified and proficient technician] QPT or [aviation maintenance training and readiness program] AMTRP" (COMNAVAIRFOR, 2017, Chapter 10.1.3.2.7). USN personnel fall under the QPT program while USMC personnel fall under the AMTRP. These two programs are integrated via the Naval Education and Training (NAVEDTRA) Personnel Qualification Standards (PQS).

Directed by the *Personnel Qualification Standards Program* (OPNAVINST 3500.34), "PQS are structured training syllabi that delineate the minimum knowledge and skills an individual must demonstrate before they are qualified to perform specific maintenance or administrative duties" COMNAVAIRFOR, 2017, Chapter 10.1.2.5). A typical training syllabus consists of reading publications that govern the task at hand, executing various practice evolutions of a task, executing several iterations of the task in an operational environment, taking an exam that covers the topic, and obtaining digital signatures from qualified personnel who serve as verification that the trainee completed each task. Maintainers complete the requisite PQS associated with the qualification they are pursing. A maintainer's profile is comprised of all previous and current qualifications, to include the current status of qualifications the maintainer is in the process of completing. Additionally, ASM is the primary database used by both USN and USMC Organizational (O-level) and Intermediate Level (I-level) personnel.

An O-level activity is one that is authorized to conduct level 1 repair, which includes inspecting, servicing, adjusting, replacing parts, and minor repairs of aircraft. These are units that operate aircraft or aeronautical equipment. For example, an F/A-18 squadron is considered an O-level activity. An I-level activity is one that conducts level 2 repairs, which include repair of aircraft components and subassemblies. For example, a Marine Aviation Logistics Squadron (MALS) or an Aircraft Intermediate Maintenance Department (AIMD) are considered I-level activities. To further aid in the understanding of maintenance capabilities, consider maintenance on a car. An O-level activity can be compared to a motorist who changes their own oil and can successfully complete minor repairs at home. An I-level activity can be compared to a transmission shop who specializes in rebuilding automotive transmissions.

3. Aircraft Tow Crew Qualifications

As mentioned in Chapter II.B, a tow crew is composed of six individuals: tow crew director, tow crew driver, brake rider, two wing walkers, and a tail walker. Of the six individuals, only three receive a formal qualification and training through the IST:

- Tow Director
- Tow Driver
- Brake Rider

An example of a tow crew director training syllabus and be found in Appendix A. Tow Crew Director Training Syllabus Example. Training syllabi for the tow driver director and brake rider are similar to that of a tow crew director. However, they have different requirements specific to the qualification. Note that the only member of the tow crew that requires any prerequisite qualification is the tow crew director, who also is required to hold an active tow driver qualification.

E. VIRTUAL ENVIRONMENTS

A virtual world, VE, is “[an] artificial space in some way separated from the physical world” (Stankovic, 2015, p. 9). The military, among others, has found a multitude of significant uses for VEs by means of VR. VR systems (discussed further in Chapter II.E.1.a) are a means of interacting with VEs. VR system technologies have rapidly developed over the last decade, lowering the barriers to entry for the average consumer and creating demand for an ever-expanding VR market. A recent report from Futuresource Consulting expects the VR market to reach sales of 98.4 million by 2023 “generating an installed base of 168 million units with a worldwide population penetration of 2%” (Rogers, 2019 para. 1). Another market forecast by ABI research predicts the VR market will continue to grow at a rate of 45.7 percent per year, obtaining a market value of $24.5 billion by 2024 (Nagel, 2020).

One reason for this major increase in growth is the capability of VR technologies, and more specifically the recent release of stand-alone systems that are not reliant on a personal computer to operate. VR has been able to serve as a collaboration tool for users to experience 3D objects simultaneously, which facilitates product development at a rapid rate (King, 2014). And medical industry professionals have found VR use cases to conduct training for surgical procedures (Ruthenbeck & Reynolds, 2015). Additionally, military organizations have adopted VR as a low cost, deployable, effective training solution in many areas like recruiting new personnel for service in the USN, mission rehearsal on a virtual battlefield in the Army, and cockpit familiarity training for F-35 pilots in the Air Force (Chang, 2018; Dormehl, 2019; Losey, 2019).

1. Virtual Reality

a. VR Defined

Various definitions of VR exist in academia, yet one of the most widely accepted definition of VR is that of Dr. Fred Brooks Jr. from University of North Carolina at Chapel Hill. Dr. Brooks defines a VR experience as “any in which the user is effectively immersed in a responsive virtual world” (Brooks, 1999, p. 16). A key takeaway from Dr. Brooks’ definition of VR is that the user interacts with the VE. In VR, we ideally want the user to experience a heightened sense of presence, which is “a state of consciousness, the (psychological) sense of being in the virtual environment” (Slater & Wilbur, 1997, p. 605). The goal of VR is to provide the user with an experience that draws them away from the real world and into a virtual one. Therefore, we can say that VR is “an interactive, immersive and realistic, three dimensional computer simulated world” (Davis et al., 2014, sec. 1).

b. Virtual Reality Shortfalls

Although VR is a promising technology with many use cases, there are still several limitations that exist within the discipline. Shortfalls to be discussed include the uncanny valley effect, cybersickness, and field of view (FOV) limitations. Of note, the limitations discussed in this paper are some of the most the notable shortfalls in VR, but not an all-encompassing list.

(i) Uncanny Valley

A user’s interaction with VR is dependent upon the human perceptual process, which is extremely complex in nature and is composed of emotion, cognitive, and rational components (Stankovic, 2015). As developers emphasize realism in the creation of VEs, the user experience begins to diminish due to the uncanny valley effect (see Figure 5). This phenomena occurs because our brain refuses to accept small discrepancies between the observed behavior in the VE and what our mind is expecting to see (Stankovic, 2015). One of the better ways of understanding the uncanny valley is looking at the relationship between empathetic response and human likeness. An empathic response is one’s emotional acceptance of what they see and human likeness is the degree to which the virtual character is representative of a real human being. “A moving animated fuzzy teddy bear is perceived as unrealistic yet cute, i.e., evoking positive emotions, while a humanoid robot aimed at mimicking realistic human behavior is at the same time perceived as creepy” (Stankovic, 2015, p. 7). In this particular case, the humanoid robot would fall under the realistic computer-generated imagery (CGI) human character (number 4 in Figure 5). Any type of character within the uncanny valley is one that registers low on the empathic response scale, which creates a sense of awkwardness between the user and the generated character. An example of rotoscopic animation (number 5 in Figure 5), is when “animators would trace live action footage projected frame-by-frame onto paper” (LaBracio & Dickey, 2017). The best way to think of rotoscopic animation is the way older cartoons were made. As each paper is shown, the “frame” is advanced. When each paper is displayed in a sequential, fluid manner, it appears as though the drawing on the paper is moving. As the virtual character approaches greater human likeness, small errors can easily be observed by the user’s brain as it gradually identifies small discrepancies between the observed behavior and the expected behavior of a real human being. The key takeaway is that higher fidelity CGI characters may not lead to the best user experience. Because of the uncanny valley effect, VR will most likely never replace real-life human experiences.

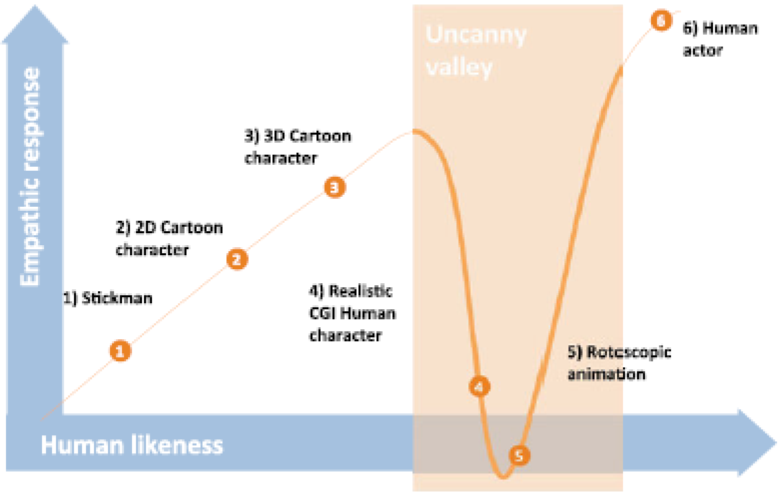


Figure 5. The Uncanny Valley Effect. Source: Stankovic (2015).

(ii) Cybersickness

Cybersickness is one of the most important health and safety issues that needs to be considered when developing any VR system because it can have profound effects on the user’s experience. Although it is a phenomenon specific to VEs, cybersickness is commonly, and incorrectly, used interchangeably with other forms of sickness like motion sickness or simulator sickness. In order to gain a better understanding of what cybersickness is, motion sickness and simulator sickness must be explored in a particular order. Motion sickness will be discussed first to provide a base to build understanding. Second, simulator sickness will be discussed, followed by cybersickness.

The human vestibular system is the mechanism a human body utilizes to provide information to the brain regarding the movement of the body and the orientation of the head in space (LaViola, 2000). Motion sickness is a form of sickness humans experience due to an unbalanced vestibular system. The vestibular system gains sensory information from the vestibular apparatus, composed of the utricle, saccule, and three semicircular canals in each ear (Vestibular Disorders Association, n.d.). Each semicircular canal is filled with a fluid called endolymph. As the head turns, inertia forces the movement of endolymph, which presses against sensory receptors in the ear canal. The vestibular system is considered balanced when the vestibular organs in both ears send symmetrical impulses to the brain. When the sensory information from each ear is different, there is an imbalance in the position of endolymph fluid within the ear canal; at this point the vestibular system is considered unbalanced. Commonly referenced as other names like seasickness, carsickness, or airsickness, motion sickness is induced by motion that is being applied to the human body. Consequently, most humans tend to experience motion sickness when they are traveling in a moving vehicle. Common indicators of motion sickness include nausea, vomiting, and dizziness (Davis et al., 2014).

Simulator sickness is a form of motion sickness that is the byproduct of human experience in a simulator. The majority of simulator sickness research has been conducted towards the effects of flight simulators on military personnel. Although symptoms of simulator sickness are similar to those of motion sickness, “[simulator sickness] SS tends to be less severe, to be of lower incidence, and to originate from elements of visual display and visuo-vestibular interaction atypical of conditions that induce MS [motion sickness]" (Kennedy et al., 1993, p. 203). Simulator sickness encompasses "various disturbances, ranging in degree from a feeling of unpleasantness, disorientation, and headaches to extreme nausea, caused by various aspects of a synthetic experience" (Stanney, 2002, p. 23). In an effort to diagnose simulator sickness, Kennedy et al. (1993) developed a quantifiable method of simulator sickness diagnosis known as the simulator sickness questionnaire (SSQ). The SSQ provides a subjective method of scoring the degree of simulator sickness one might encounter after spending time in a simulator.

Cybersickness is defined as "sensations of nausea, oculomotor disturbances, disorientation, and other adverse effects associated with VE exposure" (Stanney, 2002, p. 18). Most experts consider cybersickness as a form of motion sickness in the absence of vestibular stimulation (LaViola, 2000). This means that cybersickness can be induced solely from visual stimulation of the user. However, the exact physiological cause of cybersickness is unknown. The most widely accepted theory for the cause of cybersickness is known as sensory conflict theory. LaViola (2000) gives a great example of this phenomenon when he talks about a human experiencing a car driving simulation. While remaining stationary, the user experiences optical flow patterns that one would usually experience driving a car, driving down the road and passing buildings, road signs, etc. Visual stimuli give the user the sense that they are moving through the VE, yet the vestibular system is providing no information to the user with regard to movement of the body in space. Because the visual system is providing different information than the vestibular system, the user may experience cybersickness. Other notable, but less popular, theories of cybersickness causation include the poison theory and the postural instability theory (LaViola, 2000).

Although the effects of cybersickness and simulator sickness can be similar in nature, they are different forms of sickness. By comparing SSQ data from aviation flight simulators across various branches of military services and VE experiences from college students, effects from cybersickness and simulator sickness were found to differ in severity and symptomatology (Stanney et al., 1997). SSQ scores from VE experiences were found to be three times greater than those of flight simulators; suggesting that VE systems had a more profound effects on the user than military flight simulators. Additionally, the SSQ profile from college students showed a greater number of subjects experienced disorientation than those from the military flight simulator group.

Diagnosing cybersickness remains a difficult task due to the lack of understanding of its specific cause. A reliable and objective means of diagnosing cybersickness is still something desired amongst the VE research community. Recent studies have been conducted using heart rate motoring systems, eye-tracking technology, and electroencephalography (EEG) in an effort to identify cybersickness objectively (Davis et al., 2014). However, at this time there is no official methodology of diagnosing cybersickness objectively.

(iii) Field of View (FOV)

When humans experience VR, they do so through a head-mounted display (HMD). One of the negative aspects of current HMDs is the limitations they place on a human's FOV and other human factor issues previously discussed in Chapter II.E.1.b. In other words, FOV is defined as the "angle in degrees of the visual field," (Stanney, 2002, p. 19) The FOV includes the vertical and horizontal limits of what their eyes can see. Each eye has a horizontal FOV of roughly 140 degrees, both of which overlap to create a total, or binocular, FOV of between 180-220 degrees (Rakkolainen et al., 2017; Stanney, 2002). Additionally, the average human has a vertical FOV of about 120 degrees (Patterson et al., 2006; Velger, 1998).

In general, the larger the FOV allotted by the HMD, the more likely the HMD will present a more realistic and natural experience. This pattern occurs because larger FOVs have been found to produce a greater sense of immersion, which one could argue could also increase the degree of the user's presence in the VE (Patterson et al., 2006). Immersion is the degree to which the real world is blocked out from the user from a technical standpoint. "Immersion is achieved by removing as many real-world sensations as possible, and substituting these with sensations corresponding in the VE" (Mestre, 2005, p. 1). Presence is "[the] illusion of being a part of a virtual environment" (Stanney, 2002, p. 22). The greater the presence, the more the user feels as though they are a member of the environment. Although immersion is related to the HMD technology's ability to instill a sense of belief one has left the real world, “presence is a psychological, perceptual and cognitive consequence of immersion” (Mestre, 2005, p. 2).

Wider FOV displays allow users in VEs to utilize their peripheral vision, which improves their orientation in the VE, situational awareness, and task performance in the VE in some cases (Rakkolainen et al., 2017). Despite the average human FOV being between 180-220 degrees, the most popular current commercial off-the-shelf (COTS) VR HMDs, identified in Table 2, offer only a 110-degree FOV. Current HMD FOV is limited due to current technological shortfalls (i.e., weight of system, lens technology, computational requirements, etc.) and the human factor implications associated with those shortfalls. As mentioned by Rakkolainen et al. (2017), various requirements and parameters such as exit pupil size, latency, frame rates, and device weight place constraints on the design of HMDs. Furthermore, finding a balance between a wider FOV and resolution of the HMD is extremely difficult because of their contradictory relationship. The wider the FOV, the lower the display resolution because the pixels are essentially stretched.

Table 2. Most Popular COTS VR HMD FOV. Adapted from UL Benchmarks (2019).

Manufacturer, Model	Horizontal Field of View (in degrees)
HTC VIVE	110
HTC VIVE Pro	110
Oculus Go	101
Oculus Quest	110[a]
Oculus Rift	110
Oculus Rift S	110
PIMAX 4K	110
Sony PlayStation VR	100

[a] The Quest was released to the commercial market on May 21, 2019. To date, Oculus has yet to publish this data. However, the unofficial FOV is considered “equal to Rift” (Lang, 2019).

Another concern linked with wider FOV HMDs is the possibility of the user experiencing vection. Vection is an “illusion of self-motion, usually elicited by viewing a moving image, but also achievable through other sensory modalities” (Stanney, 2002, p. 25). Vection is something that many may experience in their everyday life. For example, consider Bob who is sitting stopped at a traffic light in his car. For some reason, the car next to Bob begins to reverse. From his peripheral vision, Bob can see the car next to him moving, but he instantly thinks his car is moving forwards. Consequently, Bob presses hard on his brake pedal in fear of drifting into the intersection. However, Bob’s car was never moving at all and remained stationary at the traffic light the whole time. The only thing that moved in this scenario was the car next to Bob, which caused Bob to endure a vection illusion of his car rolling into the intersection ahead of him.

Research has shown that wider FOV HMDs have been found to induce vection illusions more so than narrower fields of view (Stanney, 2002). The most plausible reasoning for this induction is the close relationship between the vestibular system and peripheral retina in comparison to the central retina (Stanney, 2002). Specifically pertaining to the development of VE applications, in most cases, the user will navigate throughout the VE via a controller or treadmill. The information made available to the user in the VE must correspond to the intended self-motion profile. “In most cases, VE users will not in fact be physically displaced. However, the entire pattern of multisensory stimulation to which they are exposed will specify self-motion, and in many of these cases users will experience strong vection illusions” (Stanney, 2002, p. 474). Vection can be experienced as a form of linear motion, rotational motion, or a combination of the two and it can be applied along body’s six degrees of freedom.

c. Preventing Sickness in VR

Human factor implications from motion sickness, cybersickness, and HMD FOV can be drastic and render a VR system unusable and/or adversely affect the user. Additionally, a bad first experience with a VR system could potentially deter users from wanting to use the system again. Therefore, finding a method to reduce these negative effects on the human user is extremely important for any designer of VR systems. As discussed in Chapter II.E.1.b, many of the negative attributions of VR experiences are closely related, sharing similar causes and symptomology. The close relationship between cybersickness and FOV is a particular area of interest for this project because it involves movement of an aircraft from a tow director's perspective using VR.

Over the last decade, considerable efforts have been made to limit the onsets of sicknesses tied to VR experiences. Technological advances such as the development of high-precision low-latency tracking, lightweight HMDs, with increased frame rates made a substantial impact on reducing the degree of sicknesses associated with VR systems (Fernandes & Feiner, 2016). While these advances have increased the quality of the VR user's experience by facilitating a higher degree of presence and immersion, they do not specifically address the user's navigation in the VE (Fernandes & Feiner, 2016). A persistent issue with human interaction methods inside of VEs is the fact that humans cannot move physically in the VE in the same manner they move in the real world. As one moves throughout the VE, the body remains stationary in the real world; movement is restricted, especially with regard to walking. The sensory conflict between movement within the HMD and the lack of movement in the real world create issues; especially in scenarios where the user is moving throughout the scene.

Developed by researchers from Columbia University, subtle dynamic FOV modification is a promising method of combatting sicknesses associated with users of VR systems (Fernandes & Feiner, 2016). The concept behind their research was two-fold: create an effective method of limiting a user's FOV during navigation in the VE that was undetectable to the user and evaluate its effectiveness with regard to sicknesses associated with VR applications. By utilizing an Oculus Rift DK2 HMD, Logitech Gamepad F310 controller, and the Unity3d game engine, Feiner and Fernandes (2016) developed a testbed for measuring the effects of limiting a user's FOV as they navigated the VE. They created a method of restricting the users FOV in each eye of the DK2 HMD by creating two rectangles "each of which was placed close to and in front of the center of projection of one of the two view frusta, and parallel to its base, one for the left eye, and one for the right eye" (Fernandes & Feiner, 2016, p. 203). The black rectangles served as FOV restrictors that could be modified during the user's VR experience (see Figure 6). During pilot testing, Fernandes and Feiner found that hard-edged cutouts for the FOV were too noticeable so they opted for soft-edged FOV cutouts. Pilot study participants also considered 90 degrees to be the preferred FOV and 80 degrees to be the largest FOV decrease before it became a distraction.

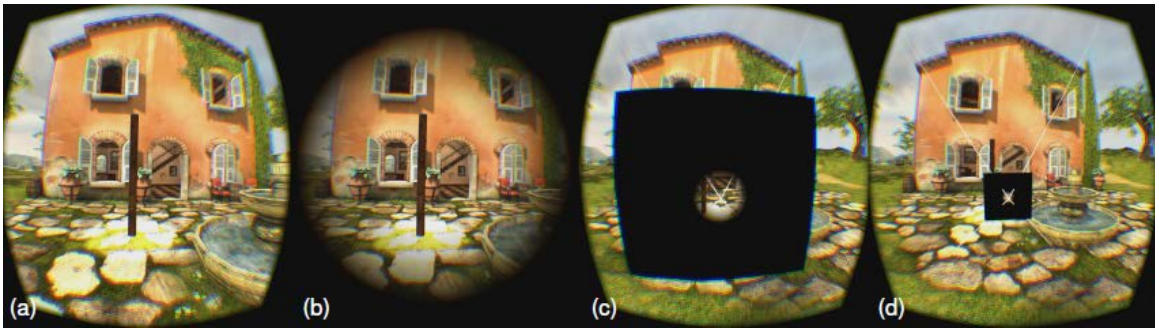


Image (a) represents the view of VE from one eye with no restricted FOV modification. Image (b) shows the same viewpoint from the VE with a restricted by 90 degree FOV, soft-edged circular cutout. While the FOV cutout is very noticeable from the desktop view, the modification is hardly noticeable when experiencing the VE through an HMD.

Figure 6. FOV Restriction Parameters. Source: Fernandes and Feiner (2016).

Fernandes and Feiner (2016) performed a two-session, within-subject user study to explore the effects of changing a seated person’s FOV in response to visually perceived motion as they navigated through the VE. The goal was to navigate to different waypoints within the VE by using the Logitech controller. When participants experienced the session using FOV restriction, their FOV would gradually decrease as they traversed through the scene and return to the initial FOV once they reached their destination. It is worth noting that while the DK2 does facilitate six degrees of freedom head tracking, the FOV restrictors were programmed to only respond to the translation and rotation of the Logitech gamepad. On two separate days, individuals navigated through the VE; without experiencing subtle FOV restrictions for one day and experiencing subtle FOV restrictions on the other. Aside from completing both pre and post-exposure SSQs, study participants verified their degree of sickness during game play after reaching five waypoints as they navigated through the Tuscany villa VE from Oculus SDK 0.4.4. Additionally, subjects answered post-session questionnaires regarding the detection of FOV change.

Fernandes and Feiner (2016) began their experiment with 32 original participants. 30 of the 32 original participants were present for both sessions. Furthermore, six of the remaining 30 participants were identified as asymptomatic to sicknesses from VR (Fernandes & Feiner, 2016). Due to these reasons, data from only 24 of the original 32 participants was used in the study. Only 12 of the 24 remaining participants were able to complete their sessions in full, while the remaining 12 terminated their sessions early due to sicknesses from VR exposure. Due to a relatively small sample size of participants who completed both sessions from the beginning to the end, Fernandes and Feiner (2016) were unable to draw any statically significant conclusions from their study. However, their results suggest a positive trend toward a better user experience when subjects explored the VE with subtle dynamic FOV modification. Under the restricted FOV session, half of the participants noticed their FOV changing while the other half did not. Additionally, those who were aware of the FOV change indicated that they would rather traverse the scene with FOV restrictions than without them.

Despite these limitations, VR technology has been proven to be a very powerful and capable technology for many industries. In most cases, VR is utilized for training or educational purposes. VR technologies have been utilized by the medical industry for dental, bone, eye, and laparoscopic surgery simulators (Ruthenbeck & Reynolds, 2015). In the military domain, VR has been utilized for various use cases to including flight simulators, the U.S. Army's Synthetic Training Environment, and the U.S. Air Force's airfield management trainer (Dormehl, 2019; Losey, 2019; "USAF Uses Virtual Reality," 2019).

d. VR Product Development

While VR has served as a vital asset for training purposes in many industries, it has also been successfully utilized as a platform for design and testing purposes (Parsons et al., 2017; Portman et al., 2015). Many products today are designed using a computer-aided design and drafting (CADD) software, which utilizes a normal desktop or laptop computer. Designers can view the product through a standard computer screen, which gives them an idea of dimensions, colors, and kinematics of the component being designed. However, one limitation of CADD is the inability of designers to interact with the 3D model in real time. “VR technology allows engineers/designers to interact, to a great extent, with the 3D model in an immersive environment and enables the testing, experimentation and evaluation of the product in full context” (Retezos et al., 2014, p. 456). A major strength of VR is that is provides a low-cost platform for companies to develop and test new product designs before committing manhours and material to a product that may never go into production. This is precisely the point of conducting this thesis research. Using VR to develop, test, and measure the effectiveness of human performance allows us to take a concept and try it in a safe, repeatable environment.

Ford Motor Corporation is a great example of a company that has recognized the true power VR can bring to the table in the early process of designing products. Ford created the Ford Immersion Lab, which allows developers to walk around a virtual prototype vehicle with a VR headset and view the vehicle from the customer’s perspective (King, 2014). While a member walks around a virtual vehicle, the view from the VR headset is projected on a large screen for other members to see. This facilitates collaboration by team members not only in the Immersion Lab but also with other product engineers in any location that has wifi access. By 2013, Ford verified more than 135,000 engineering details on 193 virtual vehicle prototypes (Ford Media, 2013).

Figure 7. Ford Immersion Lab. Source: King (2014).

Figure 8. Team Member Experiencing the Ford Immersion Lab. Source: Ford Media (2013).

Ford's Immersion Lab allows for visualization of vehicles, but fails to take advantage of the capabilities for interaction that VR provides. Bressler group is a leading design firm based out of Philadelphia, PA who focuses on designing products for customers in VR applications and developing efficient methods for users to interact with prototype, virtual products. One of their first use cases for VR product design was replacing a traditional mockup of a real residential shower unit (see Figure 9). In an empty, open room, designers were able to experience the size of the residential shower in real time. They were able to evaluate the ergonomics of the shower unit and make changes to the design based on their immersive VR experience (Murray, 2018).

Figure 9. Traditional Mock Up (left). VR Experience in Empty Room (right). Source: Murray (2018).

Aside from providing designers the experiential feedback of their prototypes, VR has also been used to objectively measure the complexity of a design with regard to the human experience. VR allows designers to data log behavior of an individual as they experience the VE. Behavior such as hand gestures, body positioning, and eye tracking can serve as quantitative data when studying an individual's behavior, which can later be used as justification to modify aspects of the original prototype to enhance human interaction with the product when it eventually goes into production. Researchers from the University of Patras in Greece developed a method to measure the complexity of prototype designs with regard to human-product interactions by using VR (Shumaker & Lackey, 2014). They created an algorithm that relied on head tracking, eye tracking, and hand tracking devices as inputs to register a human's interaction with a virtual cockpit. Using procedures from a commercial aviation after-landing procedure, they measured a subject's performance in the prototype cockpit. The idea behind this proof of concept was that the complexity score produced by the algorithm could be used by designers to modify the cockpit in a more intuitive manner; which could ultimately limit mistakes by commercial aviators.

2. Augmented Reality

a. AR Defined

AR is the "use of transparent glasses on which a computer displays data so the viewer can view the data superimposed on real-world scenes" (Stanney, 2002, p. 17). AR systems are different from VR systems in several ways. First, the two technologies have different goals. The goal of VR is to suppress a user's perception of the physical world and replace real-world stimuli with artificial stimuli to immerse the user and create an increased sense of presence in the VE (Stankovic, 2015). Unlike VR systems, ideally AR systems do not interfere with a user's perception of the physical, real-world. Instead, AR systems augment a user's perception of the real world by superimposing computer-generated artificial content for the user to see. The AR content is generally something to aid or assist the user in accomplishing a task. For example, Volvo has utilized AR to aid in the assembly of many of its components (see Figure 11). Kishino et al. (1995) coined the concept known as the virtuality continuum. The virtuality continuum is a framework that defines where both augmented and virtual reality technologies lie in relation to the real world and virtual environments. As noted in Figure 10, it is easy to see that AR lies much closer to a real-world user experience than that of VR. Because VR and AR have different goals with regard to the user's perception of the real world, there are a variety of different use cases for each technology.

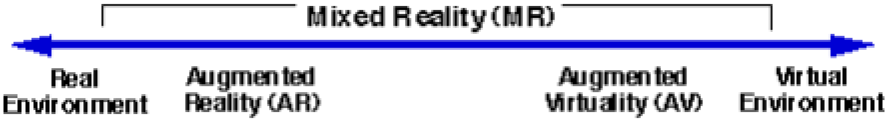


Figure 10. Simplified Representation of the Virtuality Continuum.
Source: Kishino et al. (1994).

Figure 11. Volvo Using HoloLens for Assembly.
Source: MacPhedran (2018).

Regardless of their application, the principles of operation for AR systems remain the same. Stankovic (2016) says there are three distinct steps or phases that all AR systems share when it comes to how they operate:

1. The AR system captures signals from the real world.

2. The signal gained from the real world is analyzed by the system and the corresponding virtual content to be augmented to the user is generated.

3. The AR system aligns the virtual and real signal. The computer-generated content is combined with the content from the real world and presented to the user.

“These basic phases of operation are repeated many times per second in order to generate the impression of interactive, context-sensitive, artificial content that corresponds to the user’s environment” (Stankovic, 2015, p. 128). It is important to note that the computer-generated content is context sensitive, meaning what the user sees through an AR display is based upon different inputs from the real world. Additionally, information is displayed to the user in real-time. Because AR systems provide real-time information to users, a plethora of use cases for AR technologies can be easily justified across a variety of domains. Some of the most prominent use cases for AR technologies include training in the medical and retail industries, repair and maintenance, design and modeling, business logistics, as well as for classroom education (Paine, 2018).

While Stanney’s (2002, p. 17) definition of AR specifically mentions “transparent glasses,” AR systems of today are not necessarily limited to a typical pair of glasses. Although glasses-like AR systems such as the Google Glass, Garmin Nautix, and Apple Glasses do exist, limitations of battery life, power, and entry price prevent the widespread adoption of these types of systems. The most commonly used AR device by many large commercial industries is known as the Microsoft HoloLens (see Figure 12). Some of these industries include aerospace, manufacturing, automobile, medical, and entertainment industries (Carey, 2018).

Figure 12. Microsoft HoloLens. Source: “Microsoft HoloLens Expands,” (2018).

Since its inception in 2015, the Microsoft HoloLens has played a major role in the manufacturing/repair and maintenance industries. Designers from companies like Boeing, ThyssenKrupp, and Stryker have been able to use the HoloLens to collaborate and build products up to four times faster than through traditional means (MacPhedran, 2018). Volvo has utilized the HoloLens to decrease its production time and limit mistakes by assembly-line workers. From a training perspective, Boeing has used the HoloLens to train maintenance personnel by using the AR training for on the job training. As a replacement to traditional classroom-style training, Boeing is using the HoloLens to provide text guidance and voice-overs to guide workers through maintenance tasks during a hands-on application. Boeing predicts that the use of the HoloLens will reduce the training time per trainee by approximately 75 percent when compared to traditional methods of classroom instruction and practical application (MacPhedran, 2018).

b. AR Shortfalls

Much like VR, AR has its own set of shortfalls. As AR bridges the gap between real-world human interaction and computer-generated stimuli, several issues become apparent that have profound effects on the usability of an AR system. The AR limitations this paper will discuss include: registration, latency, image quality, display brightness, effects on the human eye, and cognitive tunneling. Of note, the limitations discussed in this paper are not an all-encompassing list of limitations.

(i) Registration

One of the challenges that exists with current AR technologies is registration with real objects. Registration is the process that merges virtual objects generated by a computer with a rea- world image that is displayed by the camera (Stankovic, 2015). As users alter their viewpoints by moving their head, the virtual elements provided by the AR system must maintain their original alignment relative to the real world (You et al., 1999). A key process of registration is the identification of key features or objects in the real world to which the system needs to align and position the computer-generated stimuli to in real time. In this process, alignment is the AR system finding a point of reference in the real-world scene to properly position the computer-generated stimuli in the desired location.

Proper alignment of the computer-generated stimuli to the real world is difficult to achieve in many cases due to various factors, such as ambient light, real-world scene complexity, the form of registration used, and the computational complexity of the AR system itself. The degree of difficulty associated with fixing misalignment issues is entirely dependent on the AR system itself and its use case. The level of alignment accuracy plays a large factor in the effectiveness of AR systems because it directly impacts the usability of the system; especially in specific domains that demand accurate registration like medical industry or military. Consider an AR surgical simulation training system for medical students. The items to be simulated or generated by the AR system are a laceration that corresponds with the cutting action of the trainee and the effects of the human body from that laceration (i.e., bleeding from the laceration). If the augmented laceration and human bleeding do not occur in the same location as the trainee's intended cutting location, the usability of the AR system is diminished because it fails to provide a practical representation of what the trainee expects when performing the procedure.

In order for an AR system to achieve successful registration, the system must possess an accurate tracking system that has the ability to track six degrees of freedom (i.e., optical x axis, horizontal, vertical, roll, pitch, yaw). The six degrees of freedom are illustrated in Figure 13. Most AR systems rely on cameras as an accurate sensor of registration. However, cameras rely on "cues to aid its determination, which could either be artificial fiducial markers or real objects recognized as markers in real time computation" (Craig, 2013, pp. 39–67; Yan, 2015, p. 3).

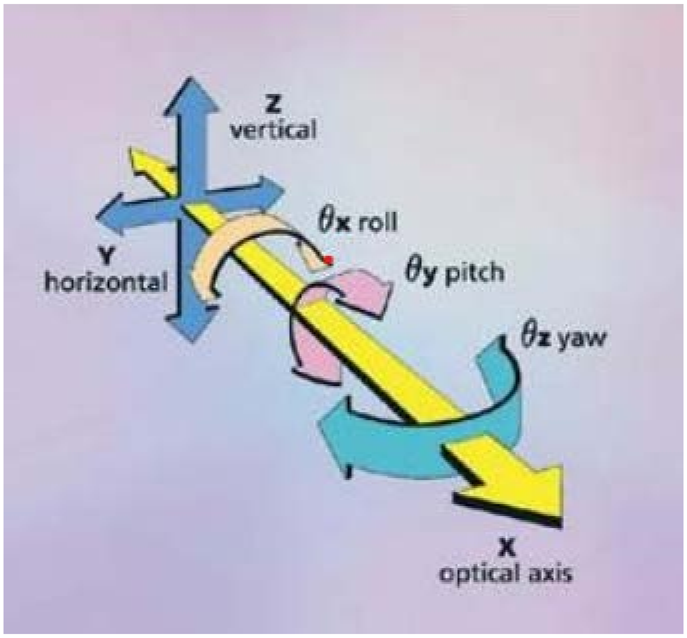


Figure 13. Six Degrees of Freedom. Source: Yan (2015).

The two main forms of image registration are marker-based and marker-less registration (Stankovic, 2015). Marker-based registration relies on AR system's recognition of markers, like 2D images or barcodes, placed in the real-world to use as reference points for computer-generated stimuli. Marker-less registration analyzes common objects from the real world like road signs, tables, or chairs using computer vision AI systems. After digesting the information in the scene, these objects serve as a map or a foundation for computer-generated stimuli to be placed.

The registration method a developer wants to use is entirely dependent on the use case. Marker-based systems require the user to "set up" the scene prior to using the AR system. This forces users to use the system in a specific environment every time. Marker-based registration works well for specific task utilization of the AR system because they are generally more accurate and reliable than marker-less systems. In a marker-based system, the system only needs to focus on specific markers in the scene rather than everything in the scene. Marker-based systems work better in motion-prone environments for this same reason. Marker-less systems work well for less task-specific use cases, but struggle in their accuracy because they force the AR system to constantly scan the scene and attempt to decipher what is important and what is not. Additionally, they require a greater amount of processing power and must have a method of connecting to a database to recognize objects in the real world, as well as being limited to areas with objects already in the database. In dynamic, or constantly changing situations, marker-less systems tend to be better because having prepositioned markers is most likely impossible. Although registration methods for AR systems have advanced over the last decade, no AR system can execute registration perfectly.

(ii) Latency

Latency is “the time delay between the actual [relative] movement of the object and the change reported by the tracker” (Stankovic, 2015, p. 92). Latency is considered the most prominent factor that influences the quality of an AR system’s ability to register computer-generated stimuli (Nabiyouni et al., 2017). For AR HMDs, the ‘tracker’ is normally in the HMD itself. While a user views the real world through the HMD, the HMD’s camera simultaneously records data from the real world and moves with user’s head. Because the head moves frequently as one experiences the real world, an increased demand is placed on the AR system to provide positioning data of the augmented computer-generated stimuli. Consistent latency can make users feel nauseous or disoriented due to the visual stimulation from inconsistent computer-generated stimuli. The rate a user moves or turns their head is related to the registration error that occurs due to latency. Little research has concluded a definite threshold for maximum latency to still provide a positive user experience. During an experiment in 2001, NASA researchers suggested a head turn speed of 10 degrees per second required a maximum threshold of 25 milliseconds (Lincoln, 2017). However, another study conducted by Jerald and Whitton (2009) suggested a human latency detection range between 3.2 milliseconds and 60.5 milliseconds (Lincoln, 2017). Since everyone moves their head differently and are affected by eye stimulation in a variety of ways, more research needs to be conducted. The key takeaway from this discussion about latency is that it can result in user frustration and ultimately render the system useless, and must be considered when creating a system or evaluating potential AR systems. The best way to combat latency is the continued progression to limit registration errors and the use of faster processors in AR systems.

(iii) Image Quality

Augmented image quality has been a persistent issue with AR displays for quite some time. There are three forms of AR displays, video see-through, partial-mirror, and grating-based (or waveguide) displays. Video see-through displays can be found on VR HMDs like the Oculus Quest, where a camera is mounted on the outside of a display panel. The HMD processes the real-world input and displays the rendered image to the user (see Figure 14). Current video see-through displays like the Oculus Quest completely block off users' vision, forcing them to rely on the video they see to digest the scene. Additionally, video see-through displays deprive users of their peripheral vision, a key component to understanding the surrounding environment. Relying solely on the image processing and display of a video see-through HMD poses a substantial risk in an application such as towing aircraft. In the event a maintainer was unable to fully understand his environment due to any of the issues previously mentioned, the resulting action could be a damaged aircraft. Therefore, video see-through displays are an unlikely candidate for use on an aircraft flight line because they simply impose too much risk on a maintainer for towing operations. For the purpose of this paper, video see-through HMDs will not be discussed further. The other display types are considered optical see-through displays, which allow the user to see the real world directly (Wagner et al., 2019).

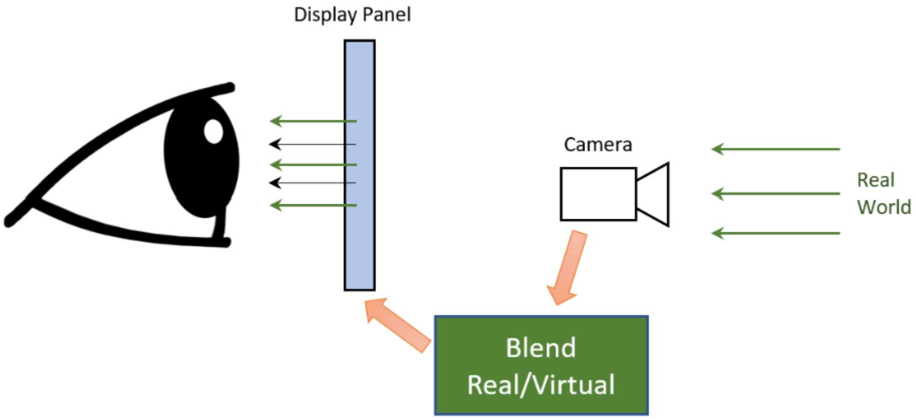


Figure 14. Video See-through Display. Source: Wagner et al. (2019).

In their recent paper, Lee et al. (2019) highlight several challenges designers face with regard to the design and development of AR glasses-like displays. Glasses-like displays are great candidates for an AR system for aircraft towing because they provide the user the ability to truly see around and through the display if necessary. These types of displays can be broken down into two categories: partial-mirror based and waveguide systems. Good image quality is achievable by using both types of systems, but the desired use case plays an important role in the effectiveness of the type of display used. For the next two paragraphs, reference Figure 15 for amplifying information.

All partial-mirror based systems involve the projection of light through a prism, while the grating-based system utilizes diffraction to guide display light along a thin piece of glass called a waveguide. Partial-mirror based systems facilitate larger FOVs and a more uniform color display than waveguide displays. Additionally, partial-mirror displays are much simpler than waveguide systems and produce higher resolution images. Calibration of partial-mirror displays is an easy process because the projected light is not redirected numerous times. However, better image quality comes at a cost. Partial-mirror displays require beam-splitters to facilitate image projection, which results in a much larger form factor. Furthermore, combiners or lenses for partial-mirror displays must be tinted for the user to clearly see the projected image.

Conversely, waveguide displays are small and sleek, yet more complex in nature. Waveguides are composed of several pieces of glass that are pressed together as one unit. The image is projected throughout the waveguide, which involves multiple angles and reflections until the image reaches the end state viewing position on the waveguide. Because waveguides reflect the image numerous times, calibration of the end state image is difficult to achieve with clarity. The constant reflection along that waveguide also results in poorer image quality than that of partial-mirror displays. However, waveguides are not as dependent on darker lenses as partial-mirror displays to successfully produce an image. Additionally, waveguides tend to perform better than partial-mirror displays in well-lit environments.

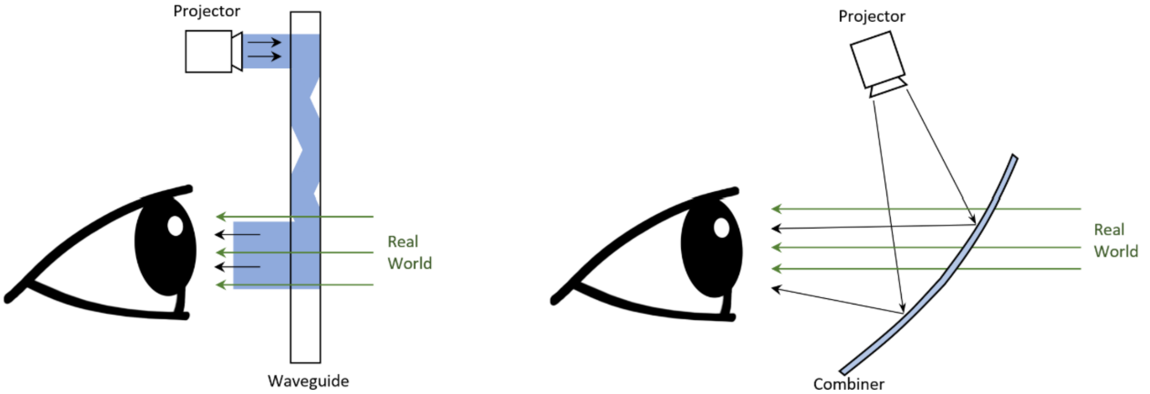


Figure 15. Waveguide Display (left) and Partial-mirror Display (right). Source: Wagner et al. (2019).

(iv) Display Brightness

Ambient light in a user’s environment effectively limits the user’s ability to see the image from the AR display; in exceptionally bright environments, the ambient light overwhelms the light of the AR system, making it difficult to see or even invisible. Lee et al. (2019, p. 11) define a quantitative guideline called an ambient contrast ratio (ACR) for measuring the image brightness requirement for AR displays with respect to the ambient light in any given environment. The ACR is a ratio that utilizes the see-through transmittance (lens transparency) and on/off state illuminance (defined by ambient light condition). In general, a 3:1 ACR is necessary for images to be recognizable, which an ACR of 10:1 yields appealing quality (Chen et al., 2017; Y. Lee et al., 2019). Additionally, ambient light is measured in units known as nits. An average living room has an ambient light of 30 nits, while a sunny day outdoors can yield an ambient light measurement of up to 3000 nits (Y. Lee et al., 2019). If the lens transparency was at 90 percent, the ambient light was in an office setting, and the desired ACR was 5:1 for adequate readability, the AR image must be displayed at over 550 nits. Due to technological challenges associated with display designs, most modern AR HMDs only display data around 200-300nits; thus the AR image would not be visible to the user (Wagner et al., 2019).

Partial-mirror based displays of today have transparency of up to about 50 percent, while grating-based displays can be as low as 10 percent (Y. Lee et al., 2019). In an effort to combat the challenges of varying degrees of ambient light, designers aim to achieve an effective ACR by lowering the transparency of the AR display lenses. Most AR HMD's use tinted visors that reduce transparency, which can be problematic in areas with low ambient light. For example, the HoloLens only allows about 40 percent of ambient light to reach the user's eye due to its tinted lenses (Wagner et al., 2019). Display brightness continues to be a challenge with AR displays because of current AR display designs, image quality restrictions, power delivery, and AR device form factor. Due to these factors, the type of display needed for the AR system will be based on its intended use case or application.

(v) Effects on the Human Eye

AR displays can have profound effects on the human eye because the eye is one of the most sensitive organs of the human body (Wagner et al., 2019). Two major factors that contribute to eye strain in AR systems: accommodation and vergence. Accommodation is the process of the pupils focusing on an object, while vergence is the eye rotating to look at the same object (Wagner et al., 2019). When these two processes are out of sync, a person can experience a phenomenon known as vergence and accommodation conflict (VAC). VAC is the result of several factors. First, the AR glasses-like displays demand a maximum eye relief of approximately 12 mm from the eye, which brings light exposure very close to the eye (Kore, 2018). Second, the illusion of depth of the computer-generated stimuli is simulated, which forces the eye to fixate on an object for a longer period of time than normal in an effort to judge depth effectively. When AR system users experience VAC, the resulting effects include nausea, headaches, and sore eyes.

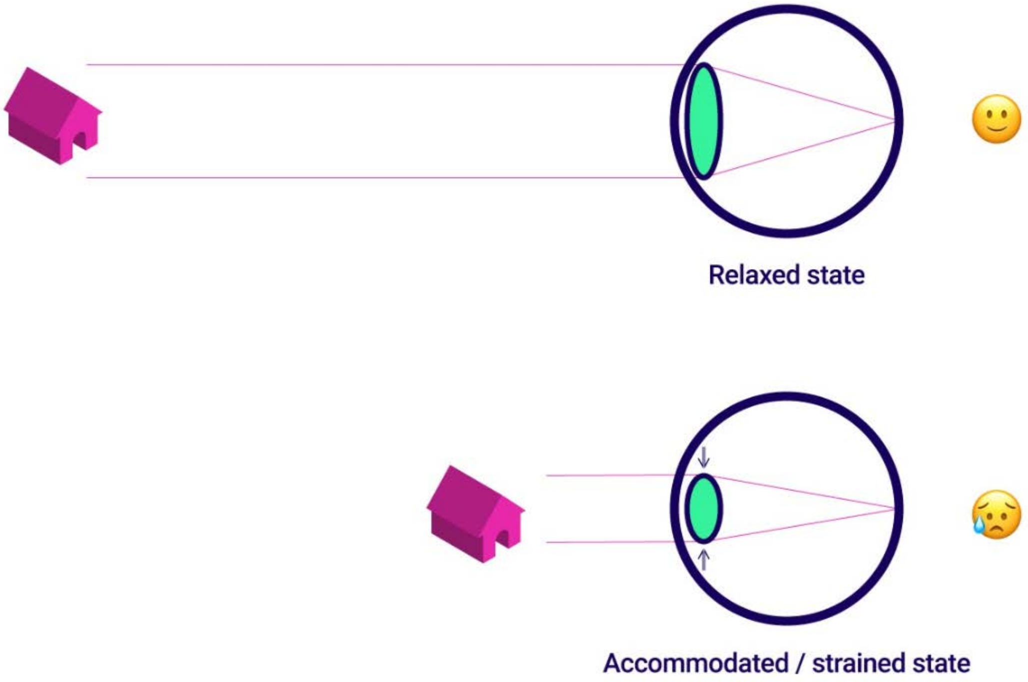


Figure 16. Accommodation Effects on the Human Eye. Source: Kore (2018).

(vi) Cognitive Tunneling

Cognitive tunneling is the act of a user becoming fixated on the data produced by an AR display, which ultimately impairs their ability of detecting events in the real world environment (Crawford & Neal, 2006). Cognitive tunneling has been linked to various causes, to include clutter, user-perceived workload, and brightness produced by an AR display (Crawford & Neal, 2006). Some of the best research pertaining to cognitive tunneling effects from AR displays comes from studies involving aircraft pilots and their interaction with heads-up display (HUD) units. Much like a human's FOV, the human attention span has a limited capacity. With respect to cognitive tunneling with HUDs, an example would be individuals performing poorly on tasks like managing a warning indicator due to their fixation with navigational data displayed on their HUD.

In 2001, Boeing's Integrated Airplane Systems Laboratory conducted a pilot study comparing pilot takeoff and landings utilizing HUDs and traditional heads-down display (HDD) units with twelve pilots (Hofer et al., 2001). Each pilot conducted 16 runs total, four takeoffs and four landings per display (HUD and HDD). Each pilot was told they could expect an occurrence out of the ordinary like a frozen gauge or a runway change during flight. Additionally, 6 of the 16 events per pilot included something that could result as a major accident if not addressed. Researchers noted that 36.5 percent of additional tasks were ignored by pilots through HUDs, while only 26 percent were ignored through HDDs. Additionally, 9 of the 36 events that would lead to accidents were neglected through the HUD, while 0 of the 36 events were ignored via HDD (Crawford & Neal, 2006). The results from this study were statistically significant and support the concept of inattentional blindness, where people "fail to notice unexpected objects direction in their FOV" (Crawford & Neal, 2006, p. 7).

F. USE OF VIRTUAL AND AUGMENTED REALITY TECHNOLOGIES FOR AIRCRAFT MAINTENANCE

Lockheed Martin, along with many other aircraft manufacturers and operators have been using VR and AR technologies over the last decade to train personnel and ultimately increase efficiency amongst their workforce (Alex, 2015; Fink, 2019). Following the path paved by industry, the DoD is recognizing that these technologies can increase maintenance efficiency, encourage collaboration between different maintenance levels, add value to current maintenance training practices, and ultimately increase aircraft readiness. This section will address some commercial applications related to aircraft maintenance, as well as some proof of concept initiatives by the USN that incorporate VR and AR technologies.

1. Aircraft Towing Training Simulator

L3Harris, well known for their driving simulators that are built for various applications such as driving fire trucks, eighteen wheelers, and emergency vehicles, released an aircraft pushback and tow training simulator around 2011. The most recent version of this platform is called PushbackSim. PushbackSim is a training platform where the trainee experiences the VE via three screens in front of them. PushbackSim allows GSE operators to practice towing aircraft in a VE, which facilitates training of new operators and practice for seasoned operators. Exact airport runway and gate layouts can be loaded into the sim to allow users to practice towing aircraft at the same airport they work at. L3Harris claims that 75 percent of the surveyed individuals who utilized PushbackSim felt safer after simulation training, and that the simulation platform reduces the learning curve for novice GSE operators by 40 percent (L3Harris, n.d).

Figure 17. L3Harris’ PushbackSim Ground Support Equipment Simulator. Source: L3Harris (n.d.).

Out of every existing product that utilizes VEs for aircraft maintenance, PushbackSim aligns the closest to this thesis work. However, PushbackSim has several limitations. PushbackSim is a single user system that only incorporates the tow driver in the towing process. This would not be a viable solution to the current problem with towing incidents in naval aviation for several reasons. The purpose of PushbackSim is to teach tow drivers, and only drivers, how to navigate aircraft out of airport parking spaces safely. This training tool neglects to incorporate the teamwork aspect of the aircraft towing process in naval aviation. Because a tow tractor driver directly follows the commands passed to him by the tow crew director, this training tool will not address the problem discussed in this thesis. In addition to the lack of consideration for other members of the towing team, PushbackSim only allows its users to practice pushing the aircraft from the front of the tow tractor. Even though aircraft are occasionally pushed with a tow tractor into their position in naval aviation, it is more common to tow aircraft from the rear of the tow tractor, pulling the aircraft in tow. This thesis will focus on pulling aircraft vice pushing aircraft to keep complexity of towing scenarios low and because of the frequency, and resulting familiarity, of towing aircraft in this manner is more common.

2. LaskerXM Ground Staff VR Training

Based out of Austria, LaskerXM worked with Tengo Interactive to develop VR training modules to airline ground service personnel in a variety of tasks which include: driver training, baggage operations, pushback operations, water service vehicles, and boarding bridge operations (LaskerXM, n.d.). These modules cover a variety of applications that ground handlers may experience while on the job. Tengo interactive is known for making each module as immersive and as real as possible.

Figure 18. Tengo Interactive Water Service Vehicle VR Training. Source: Tengo Interactive VR Training Department (2020).

3. Collaborative Augmented Reality Maintenance Assistant (CARMA)

One of the key issues squadrons face when they are conducting operations away from their home station is the lack of Depot-level, or maintenance level III support. Neither the squadron nor AIMD/MALS maintainers are authorized to perform level III maintenance; consequently, Depot-level artisans are civilian personnel. These personnel do not deploy with squadrons, which can be problematic if an aircraft requires a level III repair. The current process of fixing an aircraft when it needs level III repair is to fly a Depot-level artisan and the required equipment for repair to the squadron's deployed location so the work can be done. This process places strain on an already limited Depot maintenance support infrastructure. In many cases, there is only one subject matter expert (SME) for the specific aircraft system in need of repair assigned to each geographical region across the globe. Additionally, many level III repairs require special tooling or equipment to do the job properly; for some repairs, only one or two tools exist within the entire Naval Air Systems Command (NAVAIR) maintenance infrastructure. This process increases the downtime of the aircraft in theater, creates a cascading effect in scheduling of the Depot-level artisan, and ultimately hinders the material readiness of the fleet.

CARMA is a prototype system that was created during NAVAIR's 2019 Innovation Challenge by a team of personnel from Naval Air Warfare Center Aircraft Division (NAWCAD) and Naval Air Warfare Center Training Systems Division (NAWCTSD). CARMA facilitates collaboration between the two entities via a live video feed, PDF images, audio, and text chatting using a Microsoft HoloLens, Samsung tablet, Windows PC, and HTC Vive to create an agnostic, collaborative tool intended for use by squadron maintainers and Depot-level maintenance personnel (Confessore et al., 2019). "Using augmented reality tools we can place a subject matter expert right with the maintainer doing repairs or whatever a maintainer needs help with fleet side, base side, wherever they need it" (NAWCAD Lakehurst Public Affairs, 2018, para. 3).

Although the feedback from maintainers who played a role in the proof of concept for CARMA was overwhelmingly positive, various limitations like FOV, gesture recognition, multi-source video viewing, latency, network security, and network capabilities prevent CARMA from being successfully implemented into the fleet

(Confessore et al., 2019; NAWCAD Lakehurst Public Affairs, 2018). Further work must be conducted to develop CARMA into a better system. However, implementing a system like CARMA in the fleet could potentially save the USN millions of dollars annually and increase readiness of all T/M/S within the NAE.

4. AR for Maintainers

Developed during the same innovation challenge as CARMA, AR for Maintainers was a proof of concept developed by NAVAIR engineers for the purpose of creating interactive maintenance publications for maintainers in naval aviation (Gray et al., 2018). Around 2012, the USN adopted a program for publication management known as the interactive electronic technical manual (IETM) – commonly referred to as IETMs since the program is an integrated set of technical manuals. IETMs is a computer application, loaded on a Panasonic Toughbook, that maintainers utilize to reference proper maintenance procedures while performing maintenance actions. While IETMs is certainly interactive, maintainers constantly need to shift their eye gaze from IETMs to the equipment while trying to navigate publications and also examine particular areas of the aircraft which makes troubleshooting more difficult. AR for Maintainers was an attempt to streamline the process of referencing publications while simultaneously working on aircraft.

Much like CARMA, AR for Maintainers utilized a Microsoft HoloLens to provide information to the user. The HoloLens displayed all the information one would find in IETMs, but also registered the location of the component in need of repair. From this point, the user could see procedures needed to make the repair, and the AR system would lead the user through the process of making the repair while looking at the system to be repaired. Using AR in place of traditional IETMs on a laptop provided a faster method of accessing relevant information to conduct a repair properly. Additionally, AR for Maintainers included a method to complete MAFs via the HoloLens; enabling the ability for workers to go in work on a maintenance action, complete the work, and sign off the MAF as complete was a notable idea that could substantially decrease the amount of time wasted on the current process of logging maintenance actions.

Developers of AR for Maintainers concluded that the technology was well-suited for I-level maintenance because the maintenance environment is less dynamic than that of the O-level. The majority of the maintenance conducted at the I-level is done at work stations or on tabletops, and maintenance procedures are generally complex in nature (Gray et al., 2018). AR for Maintainers proved to be a promising concept; however, it has yet to reach the fleet in large numbers and become an official program of record. AR for Maintainers continues to be developed by personnel from NAVAIR.

G. AR SIMULATION

1. AR Simulation Defined

It is no secret that the development of AR systems presents its own set of challenges because there are so many variables in play when trying to bridge the gap between the human dimension, computer-generated stimuli, and the real world. One method of developing a new AR system, is to purchase current COTS equipment, develop an AR software package that works with current technological hardware, and test the system in the real world under real operating conditions. In this case, modifications to the system are conducted over time throughout an extensive period of testing. This method of development may ultimately result in an effective system, but it presents several issues. Purchasing various types of equipment can be a costly endeavor, especially if it is unknown that AR is the correct solution to the problem. Additionally, current technology may not adequately meet the needs of the user, which provides the user with a system that may work in certain conditions, but still leaves a lot to be desired. Finally, testing an experimental AR system could induce unnecessary real-world risks concerning the user’s safety and/or the safety of real-world objects being use for testing purposes. Due to these issues, this method of AR development may not always be the best path to take.

A promising method of developing AR systems is through AR simulation (Ragan et al., 2009). AR simulation is the concept of building AR systems in VR, which promotes development of the AR system and provides a means of obtaining both qualitative and quantifiable data regarding the effectiveness of the AR system. VR can serve as a platform to test and optimize AR systems before they are implemented. Having complete control of the simulated environment facilitates testing of scenarios that may be too dangerous or too difficult to conduct in real-life.

A major proponent of AR simulation is Dr. Eric Ragan from the University of Florida. In 2009, Ragan and his colleagues from Virginia Tech and the University of California at Santa Barbara conducted a proof of concept experiment to prove the utility of AR simulation (Ragan et al., 2009). Their proof of concept replicated a study that was previously conducted in 1997 with an AR HUD by researchers from the NASA Ames Research Center, which had users move a ring along a computer generated path (Ellis et al., 1997).

By utilizing a cave automatic virtual environment (CAVE) and an Intersense IS-900 motion tracking system for head and hand tracking, Dr. Ragan and his colleagues replicated Ellis et al.'s study. They created a virtual ring that was connected to the Intersense IS-900 and virtual path to guide the user's movement of the ring. Fiducial markers were placed under both the ring and the path to simulate tracking for the AR system. The task was to maneuver the ring along the tube path, keeping the tube in the center of the ring as much as possible, and limit the amount of collisions between the virtual ring and tube path in the shortest amount of time.

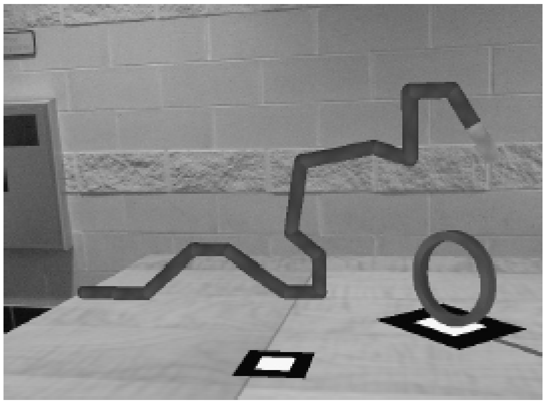


Figure 19. Virtual Tube Path and Virtual Ring. Source: Ragan et al. (2009).

They conclude their paper by suggesting AR simulation as a means of overcoming many of the difficulties that developers face when building AR systems. While Ragan et al.'s results show that AR simulation is a promising method of testing the potential effects of AR systems prior to production, their research would be more convincing if they compared their simulated AR system to a COTS AR system of at the time. Using a VR system as an AR test bed allows for perfect registration of an AR system, which facilitates the gathering of both quantitative and qualitative data regarding the effectiveness of an AR system (Alce et al., 2015).

2. AR Simulation in the Military Domain

In some instances, the scenario being tested may have a minimal probability of occurring in real-life, yet has drastic monetary and/or human-life consequences when it does occur (Geoghegan, 2015). A great example where VR was used to test the effectiveness of a potential solution to a problem was LT Brendan Geoghegan's work from the NPS regarding a ship navigation. He created a fictious navigational scenario utilizing the Unity game engine to test the effectiveness of an AR overlay to aid in a conning officer's ability to successfully maneuver a littoral combat ship. Geoghegan's experimental system enabled subjects to experience the virtual scenario through an Oculus Rift, which fully immersed the subject into the virtual environment creating a sense of presence for the subject.

By using inexpensive, COTS equipment, Geoghegan was able to successfully create a VE that replicated the processes of a conning officer during ship navigation. Within his VE, he was able to construct an AR overlay that increased a conning officer's ability to stay on the most optimal navigational track. His experiment implemented means for tracking the performance of each test subject throughout the experiment, as well as a means of measuring dependence on the AR system.

Geoghegan created the following scenarios for providing critical navigation information to the subject: auditory form only, both auditory and visual form, and visual form only; he identified these conditions as conditions A, B, and C , respectively. Condition A was similar to the then-current navigation practices of only providing information orally and served as the control condition. Each subject completed three transits out of the same channel in each condition. The channel was broken into five segments for evaluation purposes, each of which varied in degree of navigational difficulty. At the conclusion of his experiment, he found that "conning officers averaged 31.90 yards off track. Under condition B, conning officers averaged 17.41 yards off track. Under condition C, conning officers averaged 14.80 yards off track" (Geoghegan, 2015, p. 90). Furthermore, test subjects chose to keep the AR overlay on for 96% of the evolution for condition B and 98% of the time for condition C. When subjects utilized the AR overlay, they stayed less than ten yards off the perfect track 61.76% of the time. Geoghegan concluded that the AR overlay was an effective means of increasing a conning officer's ability to successfully navigate a ship.

The goal and research methodology of this project is very similar to that of LT Geoghegan's. Creating an AR overlay within the VE is a cost-effective means of developing and testing the efficacy of an AR system for towing aircraft. Most importantly, using a VE for testing an AR application is practical. The primary reason Geoghegan chose to use VR as a testbed platform for his AR system was because of the impracticality of using a real ship for his experiment (i.e., assumption of risk when navigating with the AR system, ship availability, and associated personnel requirements).

H. SUMMARY

This chapter discussed a plethora of information pertaining to the background of this thesis. After gaining an understanding of the true impact towing incidents have had on aviation in both the USN and the USMC, the current composition of a tow crew, towing process, and current training for tow crew personnel were explored. Additionally, a review of VR and AR technologies was completed, which focused heavily on limitations of both forms of technologies. With regard to the military domain, use cases for both VR (from a training perspective) and AR (from real world application perspective) continue to come to light. As both of these technologies become more affordable and software is developed to truly take advantage of their true potential, the military's interest in using these technologies continues to rise. Live training is incredibly expensive to conduct, and in many cases, only allows trainees to attempt a task one or two times. VR creates a safe environment that can be replicated, repeated, and analyzed; providing a platform to train at a lower cost with less risk. With respect to AR, current display technologies in the AR domain have yet to truly mature in a manner where they display is effective in all types of lighting conditions. However, unlike VR, one of AR’s greatest strengths is that fact that it enables users to interact with the real world. AR is something that can also be utilized in the training domain, but also a tool that could be included in daily operations like towing aircraft.

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III. EXPERIMENTAL TEST BED ENVIRONMENT

This chapter speaks to the technical applications and processes used to design, program, and simulate the AR system used for the experiment. Turning a conceptual design into something that was usable presented a number of challenges along the way. Therefore, this chapter also details the challenges we experienced and the solutions to those challenges to create the best VE to conduct feasibility testing. The initial research question of "Can AR be used to aid in towing aircraft?" was posed by the Director of the CNAF Force Readiness Analytics Group, via the NPS naval research program (NRP). The requirement for a risk-free method of feasibility testing for an AR system for towing aircraft drove us to use VR to simulate AR. Testing in VR would prevent the acceptance of unnecessary risks of towing a real aircraft and provide an objective means of measuring human performance during the towing process. We named our VE test bed ATEAR, which stands for Aircraft Towing Enhanced with Augmented Reality.

A. HARDWARE

1. Immersive Display Solution

We decided to utilize the Oculus Rift HMD (see Figure 20) as our immersive display for our experiment because of its ease of use and easy integration with the Unity game engine. Additionally, the NPS MOVES department has several of these HMDs set aside for research purposes, so having ample access to this particular HMD made it the most suitable headset for our use.

Figure 20. Oculus Rift. Source: Pino (2019).

Originally introduced to the market in 2016, the Oculus Rift provided to be a low cost, yet effective, immersive HMD that could be utilized by the average person for both gaming and research purposes. The Oculus Rift's specifications can be found in Table 3.

Table 3. Oculus Rift Specifications. Source: Alex (2018).

Display		Interfaces		Internal Tracking		Weight	Additional Features	
Resolution	1080x1200 per eye	Cable	10' detachable	Sensors	•Gyroscope •Accelerometer. •Magnetometer	470 grams	Controllers	Yes (2)
Refresh Rate	90Hz	HDMI	Yes	Tracking Area	5x5 ft		Audio	Organic Headphones
Field of View	110 degrees	USB Device	Yes				Power	Windows PC
		USB Host	USB 2.0 & 3.0					

2. Unity Integration

Over the last decade, immersive HMDs become more affordable and commercially available. Consequently, the demand for a rich and interactive VE to make use of HMDs increased significantly. Launched in 2005, Unity3d was created to expand the number of people who can develop games by providing a simple, easy to use platform that anyone could utilize to build a video game or a virtual simulation for any domain (Axon, 2016). Unity3d has become the premier game development software by game developers, as well as researchers in both the government and private organizations. According to Unity Technologies' website, Unity3d is responsible for powering 60 percent of all AR/VR content worldwide and 55 percent of new mobile games. Additionally, over 37 billion computer devices have installed Uinty3d over the last year (Unity Technologies, n.d.). Of note, Unity3d is commonly referred to as just Unity.

3. Computer System

ATEAR was built as a standalone system that only required one person to operate on one personal computer; no network is required. We built ATEAR to operate on an Asusu ROG G701VI gaming computer. The specifications of the Asusu ROG G701VI are:

- **Processor** - Intel Core i7 6820HK 2.7GHz
- **RAM –** 64.0 GB
- Operating System - Windows 10 Pro
- **Graphics Card** - NVIDIA GeForce GTX 1080, with 8GB VRAM
- **Storage –** 512 PCIE Gen3X4 SSD RAID 0 Support

B. SOFTWARE

1. Initial Design Decisions

We started with three things that ultimately drove development of our system. First, we needed to develop a VE testbed that made use of the Oculus Rift and facilitated the simulation of AR. Second, the VE needed to be constructed in such a way that human performance could be measured. Third, the VE needed to be high fidelity because the decisions made by the user would be based off of distance perception in the VE. The VE needed to be as realistic as possible to ensure decisions made by the user were along the same lines as they would be in a real towing scenario.

We worked with NPS MOVES FutureTech design team to construct and implement of the VE testbed. Once funding was secured in October of 2019, we began to discuss the design of the VE. The project sponsor had very little restrictions or specific desires, which facilitated a great amount of creativity and collaboration between members of the research team and the FutureTech team. While Unity is a very powerful program and virtually anything can be created in VR, the goal of this project was to model and simulate an AR system that could be implemented with modern technology of the real world.

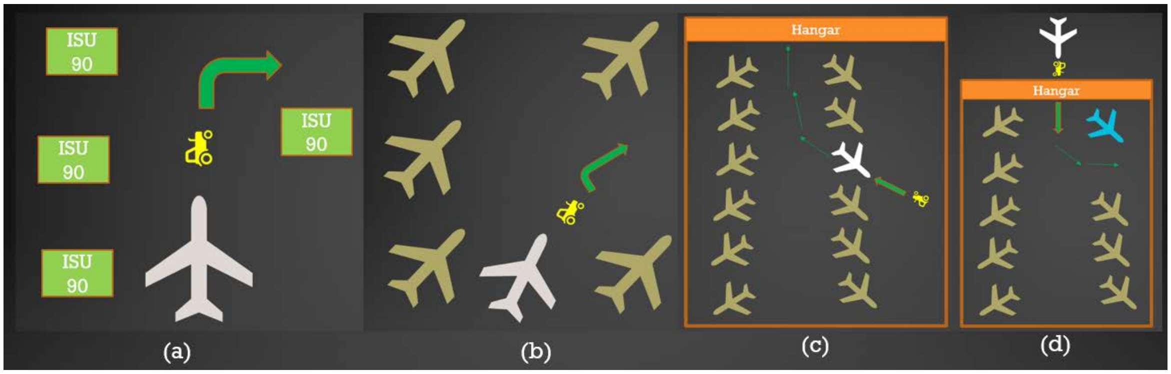
2. Simulation Development

a. Scenario Development

This section of the thesis will speak to how we designed the base environments and towing scenarios in the VE and also discuss some of the challenges we encountered during the process.

(i) Base Environments

After determining the hardware requirements and settling on using Unity as the game engine, the next step was to create a repeatable method of replicating a typical towing evolution with an F/A-18 from the tow crew director’s perspective. It is important to note that due to the scope of this project, we were only interested in the portion of the towing evolution where the aircraft was physically towed by the tow tractor. The underlying concept behind the experiment was to compare and contrast human performance between a standard view (non-AR) and an AR view. In order to ensure we were able to draw statistically significant conclusions from the experiment, we determined that each subject would need to experience 20 towing evolutions total; half of which would be from the standard view while the other half were from an AR view. To create 20 different towing evolutions, we first needed to develop a handful of base environments. These base environments would then be used as a foundation for creating 20 different towing scenarios; each scenario represented one towing evolution. The plan for our base environments is depicted in Figure 21.



(a) Aircraft is being towed forwards from the rear of the tow tractor. There are several storage containers on the flight line (ISU 90) and the tow crew needs to turn the aircraft after passing the storage container on its right. (b) Aircraft is being towed forwards and the aircraft is towed into its parking spot. (c) Aircraft is pushed from the front end of the tow tractor. In this scenario the tow tractor is continuing to push the aircraft backwards through the front of the hangar door. (d) Aircraft is being pulled by the tow tractor from outside of the hangar into the hangar. The aircraft are parked on the flight line and the aircraft is towed into its parking spot. *Note that (c) and (d) share the same base environment, but the aircraft moves in different directions.

Figure 21. Towing Environment Planning

In conjunction with the development of each environment, the team also began modeling the aircraft, the tow tractor, tow bar, and personnel involved in the towing process. The F/A-18, the tow tractor, and tow crew personnel models were imported from the Unity asset store, but the tow bar had to be created from scratch. After browsing various photographs online and examining NAVAIR 00-80T-96 for a detailed description of how the tow bar affixed to the nose landing gear of the aircraft, the team was able to accurately model the 22 ALBAR (Department of the USN [USN], 2001). Due to time constraints and additional programming requirements, we opted to not outfit the tow crew characters with cranials.

The FutureTech team utilized various photographs and videos provided by Marines from several different F/A-18 squadrons to create each base towing environment. Environments in Figure 21 a, b, and d were relatively easy for the team to create. However, Figure 21c presented a major challenge because it involved pushing the aircraft from the front of the tow tractor. Even though the overall background of this environment was relatively similar to Figure 21d, the physics of how the F/A-18 model interacted with the tow bar and the tow tractor would need to be revised. Even though tow crews push aircraft with the tow tractor during normal operations, it is less common than pulling an aircraft with the tow tractor. Additionally, creating this environment would add additional requirements to our already constrained timeline. Due to these reasons, we chose to discard the environment depicted in Figure 21d. The final base towing environments are depicted in Figure 22.

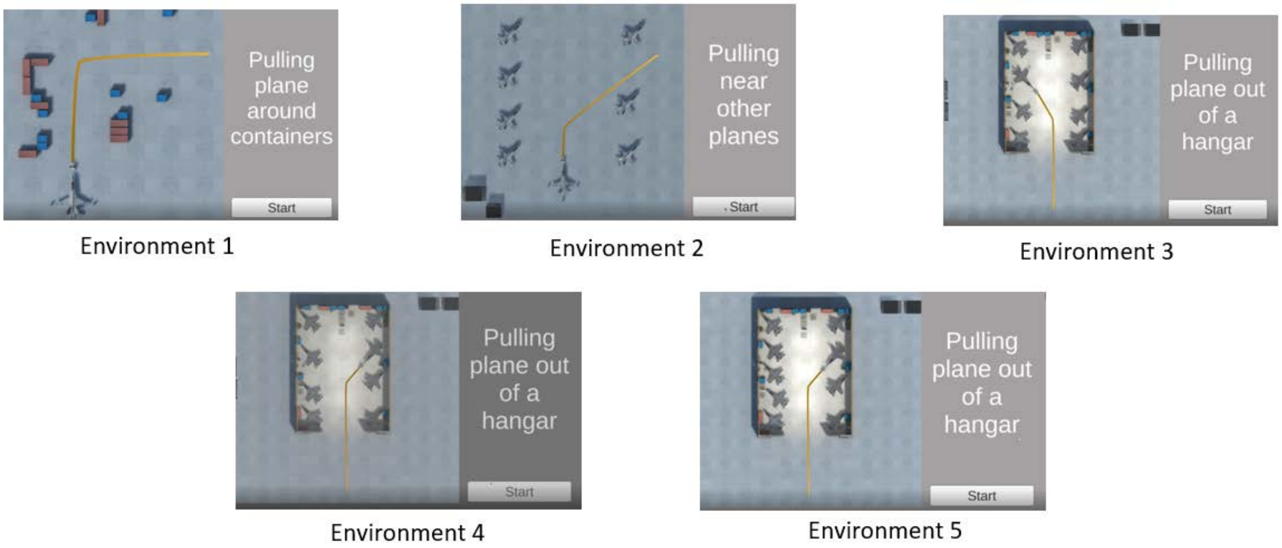


Figure 22. Finalized Towing Environments

After finalizing our base environments, we started developing different towing scenarios. Towing scenarios had to meet the following criteria:

1. Aircraft would follow a pre-programmed route to minimize subject input and so that each subject experienced scenarios in the same manner

2. At least 20 percent of the pre-programmed routes needed to result in a collision

Each scenario would effectively be the execution of one towing evolution. Because we had five base environments, we created four towing scenarios for each environment. Each towing scenario was constructed by simply changing the aircraft path of travel from the original environment. The aircraft starting point remained the same from the base environments. However, the turning angle of the aircraft was modified. By changing the turning radius of the base environment aircraft path, we were able to create hit, danger, caution, and miss scenarios for each environment. The criteria for the four types of scenarios are discussed further in Chapter III.B.2.a.3.

(ii) User Interaction with the VE

Because the aircraft was programmed to follow a pre-programmed path for each scenario, we also set a default speed for the aircraft to travel 1 unit per second. Of note, we did not establish distance metrics like feet or meters in ATEAR. Thus the speed of the tow tractor is in units per second vice meters or feet per second With regard to user interaction with the VE, the Oculus Rift HMD is accompanied by two battery powered, wireless controllers. For our application, we decided to construct the VE in a manner that only one controller was necessary. However, we did ensure that left handed users could use the left hand controller and right handed users could use the right handed controller. Each controller has six buttons that can be programmed to any function in the VE (see Figure 23). We decided that the following button assignments were the most natural and ergonomic way for subjects could use the controllers:

- **Menu Selection** (RH- A button/ LH- X button) – a way for the user to navigate through the user interface of the VE (i.e., begin scenarios and answering questions during the experiment).
- **Stop Aircraft** (RH- B button/ LH- Y button) – this button would be pressed if the subject felt that the aircraft was going to collide with another object during the scenario in which they were experiencing. Simultaneously when

this button is pressed, an auditory whistle would be heard in the headphones of the HMD.

- **Navigation** (thumbstick) – the thumbstick would allow the subject to move about the scene to gain different vantage points to determine if the aircraft was going to collide with something.
- **Change Aircraft Speed** (trigger)– the trigger implemented the ability for the subject to alter the aircraft speed. This speed would be utilized as a means of measuring their confidence throughout a scenario.

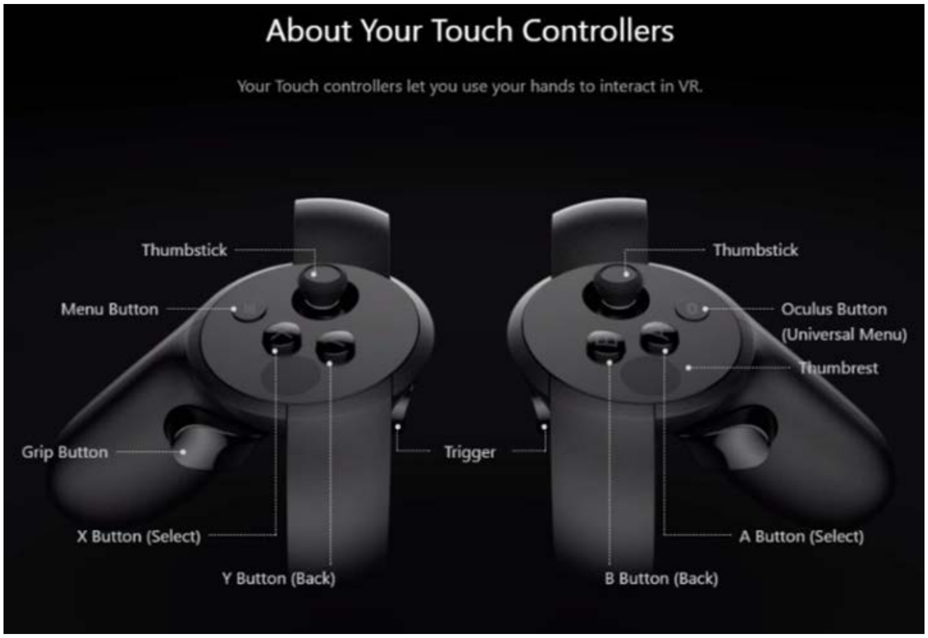


Figure 23. Oculus Rift Controller Interface. Source: Orland (2016).

(iii) Navigation

After the modeling of the essential items was complete and our VE interaction was finalized, we focused our efforts to the next challenge, navigation. As we discussed in Chapter II.E.1.c, navigation in VR can lead to various forms of sicknesses because of the sensory conflict between a user's stationary body in the real world and movement throughout a VE in VR. Because we chose to design the system around the view point of a tow crew director, the user would be virtually walking backwards in the VE, and the aircraft would also be following the same direction. We also needed to allow the user the ability to navigate in the scene, similar to how they would in the real world, to change their vantage point as the aircraft was moving along its path. Note that the intended path for the aircraft in each scenario is not all a straight line; the aircraft turns as well. Additionally, an attribute native to VR HMDs would complicate the matter; the user would have the ability to turn their head in the VE, further increasing the risk of the user having an uncomfortable experience.

In the real world, a two crew director can freely navigate around the aircraft. However, they generally remain around the front half of the aircraft because their primary responsibility is giving directions to the tow crew driver. Due to this reason, we built a path for the tow crew director to move along during the towing evolution (see Figure 24a). The parabolic path for tow crew director navigation was beneficial in two ways. First, it allowed us to use the aircraft as a foundation for movement of the user. We set the left and right limits for movement in line with the left and right wingtip of the aircraft. Second, it simplified the user interaction with the Oculus Rift controller by only allowing left and right inputs from the joystick.

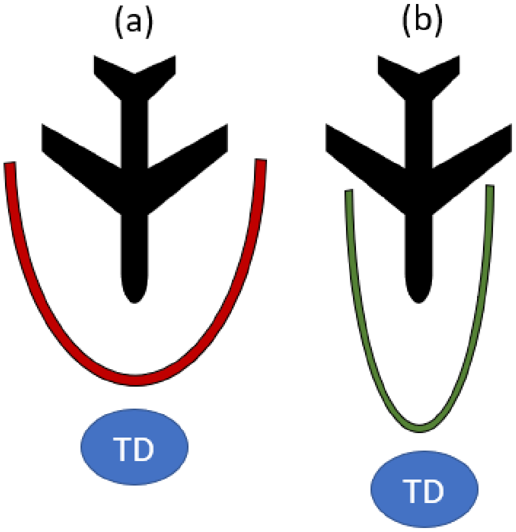


Figure 24. First and Second Iterations of Tow Crew Director Navigation Restriction

After conducting several test scenarios of navigating in the VE, we were impressed with how minimal the effects of compounded movements were on the user experience. The 110 degree FOV in the Oculus Rift prevented us from experiencing any sort of vection as the test scenes progressed. Additionally, head movements during navigation in the VE caused minimal discomfort; implementing FOV restrictors like those discussed in Chapter II.E.1.c was unnecessary. Even though our first tests with navigation were successful, there were several issues we wanted to address. The initial parabolic curve was set too wide and forced us to be in a further position away from the cockpit of the plane than what was desired. We decreased the width of the parabolic curve, which placed the tow crew director is a more favorable, and realistic, position (see Figure 24b). Second, the navigation speed was too high and did not replicate the speed of a human being walking. We ended up decreasing the movement speed for the user as well, which also made navigation feel more natural.

As previously mentioned, the tow crew director path was tied directly to the wing tips. We did this for the simplicity of programming for multiple scenarios. However, one of the consequences of doing so is that for some scenarios, the user is unable to move to the most desirable position. For example, consider the scenario in Figure 25. The subject (tow crew director) finds themselves on the outside of the tow tractor as the tractor makes a right hand turn. However, there is a storage container on the right side of the aircraft that could pose a threat. The subject naturally wants to navigate to the right side of the aircraft to gain a better view of the aircraft’s right wing tip in relation to the storage container. Because the subject is fixed to the parabolic path, they are unable to navigate to the position they want to be in until the aircraft begins to turn. By the time the subject is able to navigate to their desired position, the aircraft may have already hit the storage container.

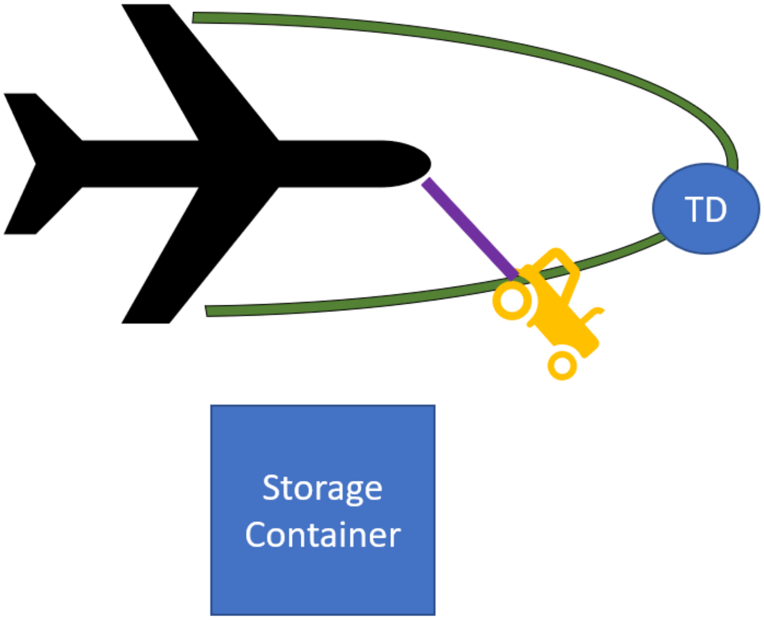


Figure 25. Problematic Tow Crew Director Path Diagram

The issue outlined in Figure 25 is something we ended up having to accept due to the time constraints of completing the VE. However, as a partial solution to the problem, we enabled the tow crew director to walk through solid objects (i.e., the tow tractor, storage containers, etc.) so the subject could still see the aircraft as they navigated about the restricted path (see Figure 26 and Figure 27).

Figure 26. Tow Crew Director Forced to Walk Through Storage Container

Figure 27. Tow Crew Director Forced to Walk Through Tow Tractor

b. Human Performance Metrics

Primary performance measures used to test our hypothesis were collision detection rate, mean stopping distance, and confidence levels.

(i) Collision Detection Rate

The collision detection rate is simply the rate in which the subject accurately predicted a collision was going to occur. If the scenario was programmed as a collision scenario, we would expect subjects to blow the whistle for non-collision scenarios. For scenarios designated as caution or miss, we anticipate that subjects would refrain from blowing the whistle and allow the aircraft to move along its path.

(ii) Mean Stopping Distance

The mean stopping distance was a major topic of discussion during the development of ATEAR. We utilized simple time (i.e., sim time) and the last known speed of the tow tractor stopping distance calculations. We defined success as subjects being able identify a collision faster when using the AR view than they would without. Because accidentally towing an aircraft into something has such drastic ramifications to aircraft readiness, we would want the movement of the aircraft to cease as early as possible. The stopping distance for one scenario is defined as:

$$Dist = LastKnownTractorSpeed\,(SchedCollisionSimTime - WhistleSimTime)$$

The experiment would be a counterbalanced design in which some subjects would complete a scenario using the AR view, while others would complete the same scenario using the standard view. The experimental design is discussed further in Chapter IV. The mean stopping distance for AR view subjects in a scenario would be compared with the mean stopping distance for subjects with the standard view in the same scenario.

(iii) Confidence Levels

We wanted to measure each subject's confidence in their ability to predict a potential aircraft collision for each scenario from both an objective and subjective standpoint. To get an objective measurement, we allowed subjects to control the speed of the aircraft movement in 10 of the 20 scenarios by using the trigger of the Oculus Rift controller to modulate the tow tractor speed. If the subject pulled the trigger all the way in (i.e., max speed), the speed of the tow tractor was raised to 2 units per second (double the default speed). The CSV file captured the tow tractor speed every 0.5 seconds. We assumed a higher average tow tractor speed and minimal variation in tow tractor speed would indicate a higher degree of confidence. The speed values from the tow tractor would be used to measure each subject’s average speed and standard deviation of speed for each scenario.

To measure each subject’s subjective confidence, we implemented confidence questions at the conclusion of each scenario in the VE. There were three ways a scenario could end: subject ends the scenario by blowing their whistle, aircraft collides with an object and the whistle is not blown, and the whistle is not blown and no collision occurs. The last two instances result in the scenario ending with no input from the subject. As a result, we had two different outcomes that drove our confidence questions.

- Question A – When you blew the whistle, how confident were you that a collision was going to happen? *(trigger: whistle blown, regardless of programmed collision)*

- Question B - Before the scenario ended, how confident were you that the aircraft would finish its route collision free? *(trigger: whistle NOT blown, programmed collision)*

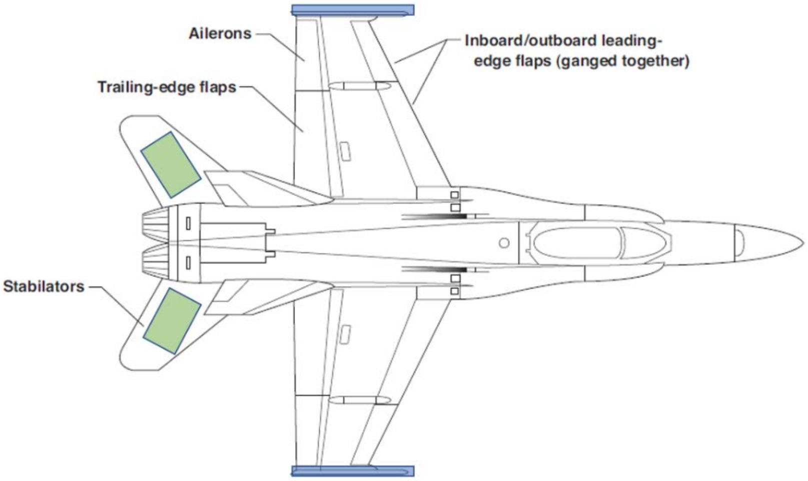
In order for subjects to answer each question, they placed a marker on a linear analog scale (see Figure 28). The slider bar corresponds to a 1-10 linear analog scale, low to high, respectively. However, the value captured by the CSV file is coded as a float, which yields a decimal. We intentionally did not incorporate a snap to grid function on the slider bar (where the input finds the nearest whole number and locks onto that value) nor did we show the subjects their selected values in order to ensure we had variability in our data.


When you blew the whistle, how confident were you that a collision was going to happen?

Figure 28. Confidence Question User Input

c. AR System Development

The intent behind the AR system was to develop a simple, easy way of providing the tow crew director information regarding the aircraft's position relative to other surrounding objects. We wanted to design the AR system in such a way that it could be developed and implemented in the real world with current AR technologies. For many towing collisions, the point of impact on the aircraft is either one of the wing tips or the horizontal stabilators (see Figure 29).



Blue boxes mark location of wing tips and green boxes mark horizontal stabilators

Figure 29. F/A-18 Flight Control Surfaces. Adapted from Brown & Schaefer (2013).

Because all of our scenarios consisted of the aircraft being towed from the rear of the tow tractor, all of the scenarios were programmed in such a way that collisions would occur on only the wing tips. Due to this attribute, we designed an AR system that only focused on the wing tips, not the horizontal stabilators. Our simulated AR system locks onto simulated sensors placed on the wing tips of the aircraft (see Figure 30). The system provides both auditory and visual indicators to the tow crew director. The wing tip will illuminate green and provide no auditory tones when there are no objects within three feet of the wing tip. Once a wingtip sensor detects an object within three feet, the respective wing tip color will change to yellow and an auditory beeping tone will begin to play out of the respective side of HMD headphones. If the wing tip sensor detects an object within six inches, the wing tip color will change to red and the frequency of the auditory tone increases.

Figure 30. Simulated AR System Wing Tip Indicators

When the tow crew director positions themselves on one side of the aircraft, their vision is occluded by the fuselage of the aircraft; meaning they cannot see the wingtip on the opposite side they are standing on. To provide the tow crew director information regarding the status of the occluded wing tip, we made the AR track visible through the aircraft (see Figure 31).

Figure 31. AR System Occluded Wingtip Visibility

In addition to the tracks on the wing tips, the AR system is designed to alert tow crew directors about a potential impact when the aircraft is out of their FOV (see Figure 32). In this particular instance, the aircraft under tow is the left of where the tow crew director is looking. The warning indicator on the left is telling the tow crew director that one of the sensors has detected an object in close proximity to the aircraft. As the tow crew director orients their head towards the left and the aircraft comes within their FOV, the warning indicator will disappear.

Figure 32. Warning Indicator for Alert Outside of FOV

d. ATEAR Version 1

The first version of ATEAR was completed by the MOVES FutureTech team around the second week of January 2020.

(i) Home Screen

ATEAR is comprised of a home screen, that serves as the main menu of the system (see Figure 33). At the conclusion of each module, the system was designed to return to the home screen. During the initial design process, we contemplated building ATEAR to run all 20 scenarios sequentially without any input from the proctor. However, the experimental design would be a counter balanced experiment to compare performance from the standard view and the AR view. Moderating the experiment via the home screen would be easy for the experiment proctor and designing the home screen, as such, saved an ample amount of time programming. The home screen is only visible through the desktop display organic to the laptop that is running ATEAR and the home screen is the only screen that the subject cannot see in the HMD display. For all other aspects of ATEAR, the display from the HMD is mirrored onto the desktop display. All fields/selections in the home screen are used to prepare the next set of scenarios for the subject to experience. While the home screen is active, “Please wait while we get you set up,” is displayed to the subject in the HMD. The home screen is comprised of the following fields: subject ID, Is AR On, Can Control Tractor Speed, Tutorial, Scenario Sets 1-4, and Exit.

- Subject ID – the proctor enters the subject’s ID (a number utilized during the experiment to maintain subject anonymity and represent the subject for data analysis).
- Is AR On – if selected, turns the simulated AR system on.
- Can Control Tractor Speed - if selected, turns on the trigger on the Oculus Rift controller so the subject can modulate the tow tractor speed.
- Tutorial – starts ATEAR tutorial.

- Scenario Set X – selects the desired set of scenarios for the subject to experience.
- Exit - exits the ATEAR program.

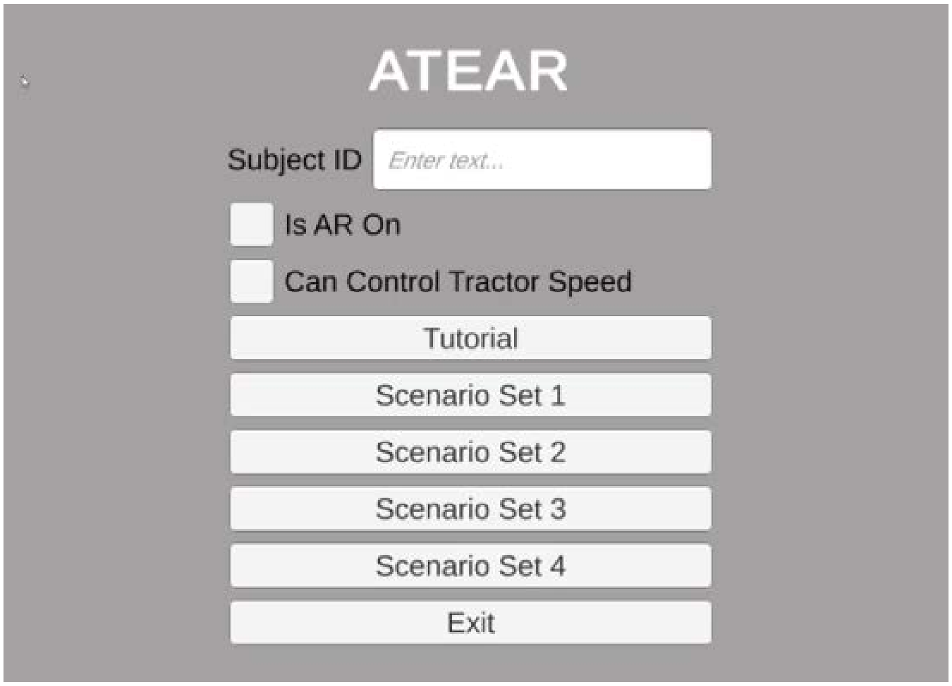
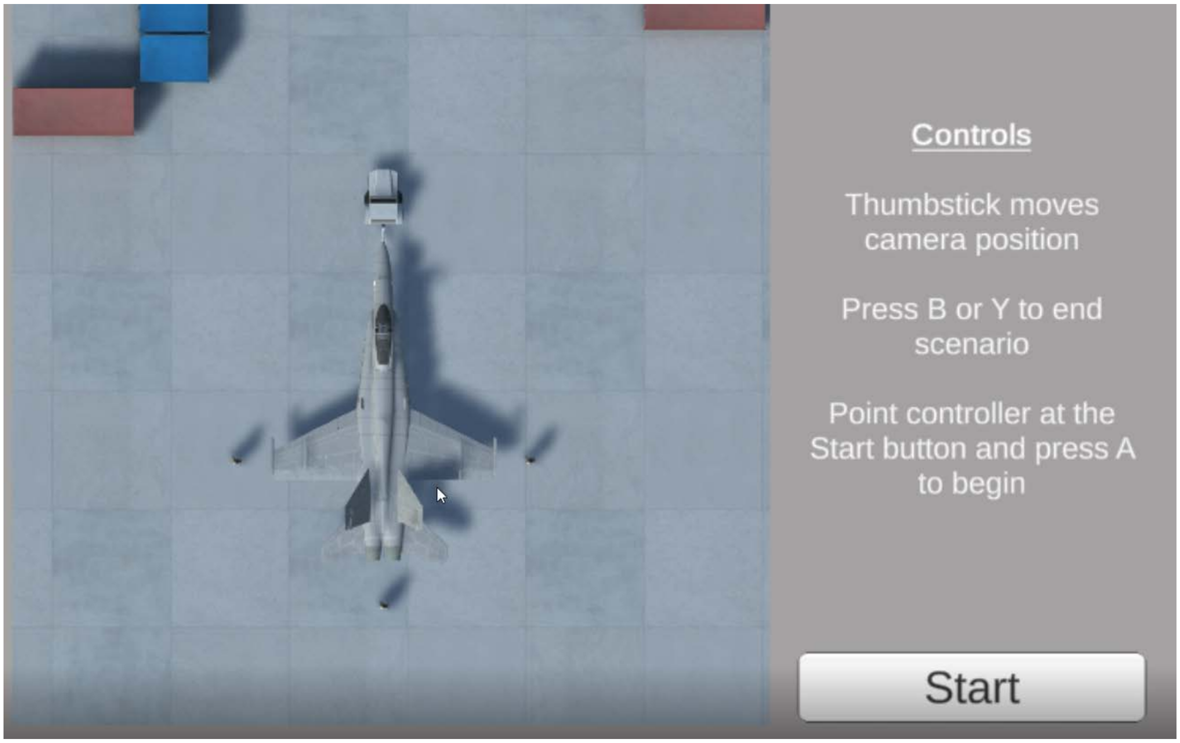


Figure 33. ATEAR Home Screen

(ii) Tutorial

The tutorial serves as a familiarization with the ATEAR system. Before starting any scenarios, each subject executes the tutorial. The tutorial is comprised of three modules: introduction to controls, the AR system, and tow tractor speed control (see Figure 34 - Figure 38). Each module consists of a screen that contains instructions to the subject, followed by the execution of those controls in environment 1.



Controls

Thumbstick moves camera position

Press B or Y to end scenario

Point controller at the Start button and press A to begin

Figure 34. Tutorial: Introduction to Controls

After selecting “Start,” the subject is placed in the tutorial environment to familiarize themselves with a typical scenario. All equipment and personnel remain stationary during this module. Subjects can navigate around the aircraft and move their head around. There is no specific time set to end this module; the module concludes when the “B” button is pressed on the controller.

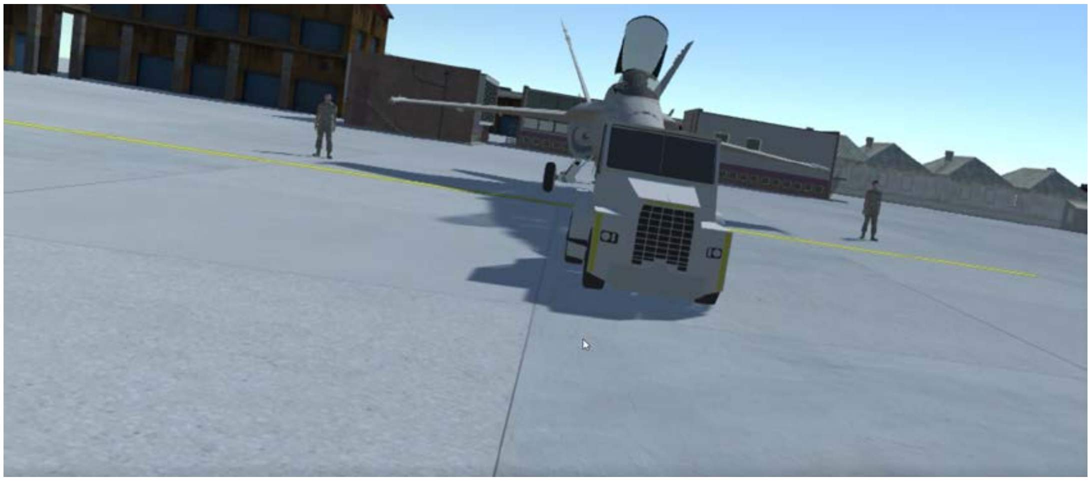
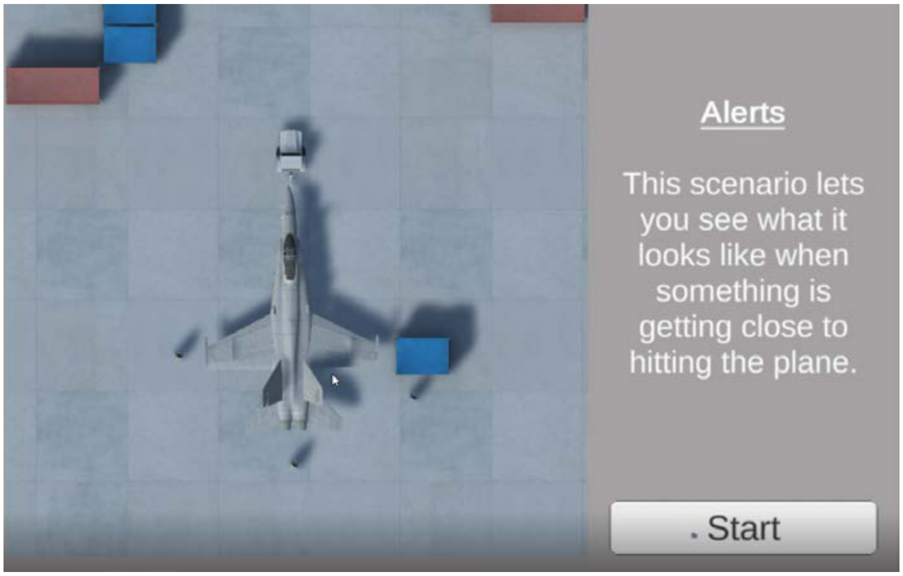


Figure 35. Tutorial: Standard View in Environment 1

The next module familiarizes the subject with the simulated AR system in ATEAR.



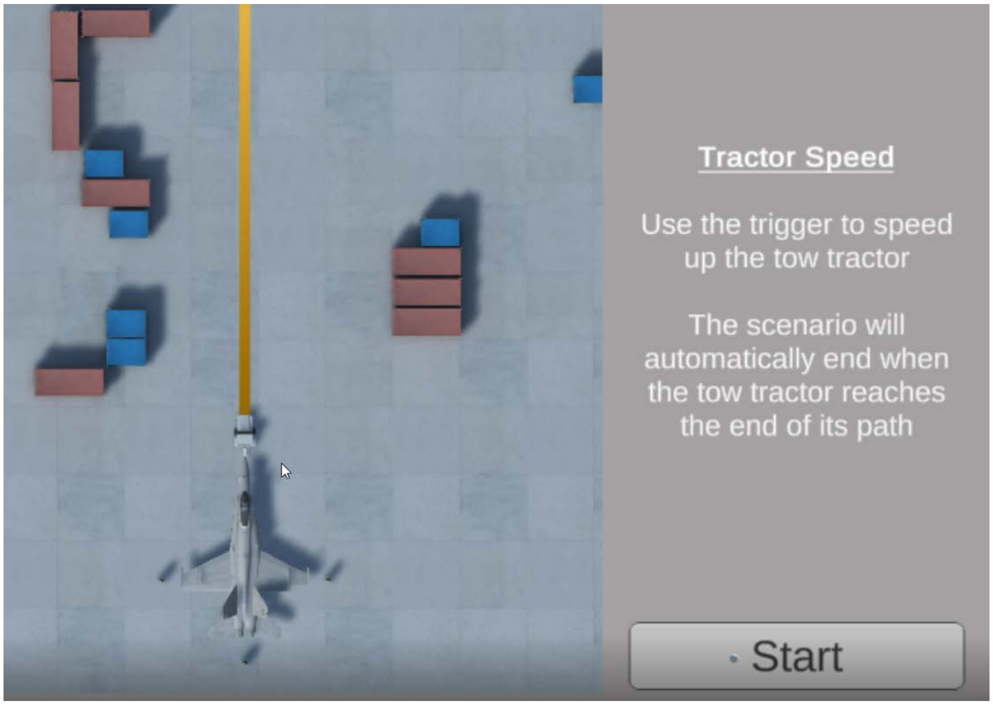
This scenario lets you see what it looks like when something is getting close to hitting the plane.

Figure 36. Tutorial: Introduction to AR Display

After selecting “Start,” the subject is placed in the AR system module.

Figure 37. Tutorial: AR View in Environment 1

Just like the first module of the tutorial, the equipment and personnel in the scene remain stationary. The subject can navigate around the aircraft. The right wing of the aircraft is purposely placed within three feet of a storage container to trigger the yellow indicator of the AR system. To end the scene, the subject must press the “B” button. The next module teaches the subject how to modulate the speed of the tow tractor.


Tractor Speed

Use the trigger to speed up the tow tractor

The scenario will automatically end when the tow tractor reaches the end of its path

Figure 38. Tutorial: Introduction to Speed Control

After selecting “Start,” the subject is placed in the tow tractor speed control module. This module looks the same as Figure 35. However, the equipment and personnel in the scene are moving. The subject can navigate around the aircraft, move their head, and change the speed of the tow tractor by modulating the trigger on the Oculus Rift controller. The module will automatically conclude once the tow tractor has finished it’s predetermined path.

(iii) Scenario Layout

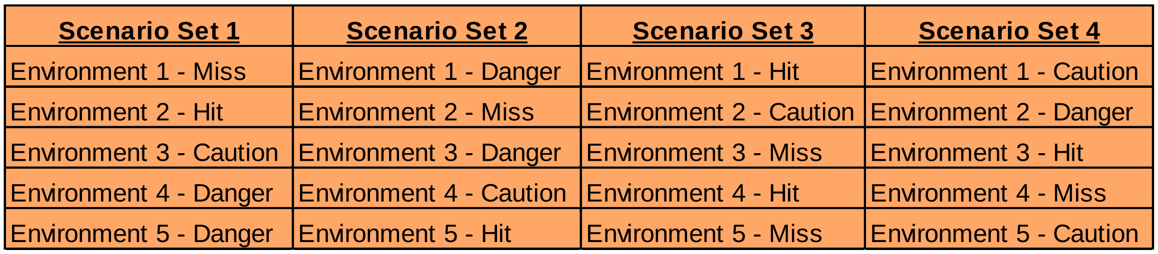
We wanted to ensure there was some variability in each scenario to obtain meaningful data from the experiment. If the aircraft was programmed to collide with something for all 20 scenarios, subjects would most likely anticipate collisions occurring and it would be difficult to conclude that the AR system was or was not an effective. We chose build scenarios based off of the following scale (in order of severity): hit, danger, caution, and miss.

- Hit - the aircraft path was programmed to collide with something else during the scenario. Hit scenarios were the only scenario types where subjects would witness a collision and the only scenarios in which a stopping distance could be calculated.

- Danger - the aircraft was close enough to warrant a whistle in the real world (i.e., a wing tip approximately six inches from a container).
- Caution- the aircraft was within three feet from an object.
- Miss – the aircraft was greater than three feet from an object.

All four types of scenarios were built using the five base environments (see Table 4). When the ATEAR proctor clicked the desired scenario set from the home screen, the subject would complete each scenario within that set, in the order depicted in Table 4.

Table 4. ATEAR Version 1 Scenario Set Break Down



Scenario Set 1	**Scenario Set 2**	**Scenario Set 3**	**Scenario Set 4**
Environment 1 - Miss	Environment 1 - Danger	Environment 1 - Hit	Environment 1 - Caution
Environment 2 - Hit	Environment 2 - Miss	Environment 2 - Caution	Environment 2 - Danger
Environment 3 - Caution	Environment 3 - Danger	Environment 3 - Miss	Environment 3 - Hit
Environment 4 - Danger	Environment 4 - Caution	Environment 4 - Hit	Environment 4 - Miss
Environment 5 - Danger	Environment 5 - Hit	Environment 5 - Miss	Environment 5 - Caution

(iv) Scenario Flow

At the beginning of each scenario, the objective of the scenario is displayed (see Figure 39). The type of tow is displayed on the right hand side of the screen. As the tow tractor and aircraft are programmed to follow a predetermined path, the intended path is displayed via a yellow line. Because the subject cannot alter the path of the tow tractor, the path is shown to give them an idea of what to expect in the scenario.

Figure 39. Scenario Objective Screen

After selecting “Start,” the scenario begins. At the conclusion of the scene (whistle blow, aircraft collision without whistle blow, or the scene ends on its own), the respective confidence question is asked to the user. While the confidence question is displayed, the scenario is paused in the background. After selecting the “Proceed” button on the confidence level question, the scenario complete screen is displayed (see Figure 40). This screen provides feedback to the subject regarding their performance on the scenario and consists of a top down view of the scenario the subject just completed. For scenarios in which the subject blew the whistle, the scenario will resume playing and the aircraft will move until it reaches its scheduled stopping point..

For scenarios in which the whistle was blown by the subject, a black outline of the aircraft will appear at the aircraft’s location in the scene at the moment the whistle was blown or ATEAR stopped the scenario (see Figure 40).

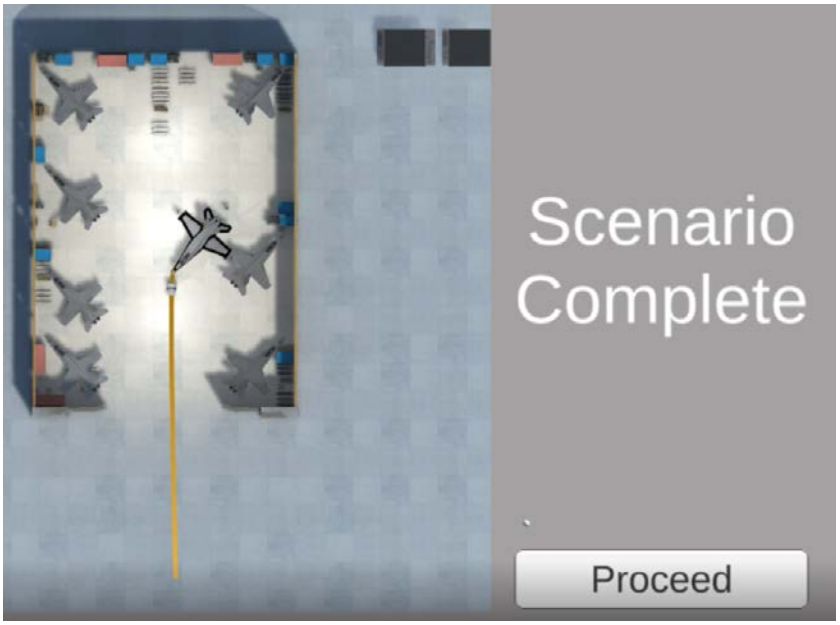


Figure 40. Scenario Complete Screen

For scenarios where a collision occurred, the impact location will be marked with a red “X” (see Figure 41). Of note, the red “X” is difficult to see in this picture due to the size requirements to fit this page. In ATEAR, the red “X” is more visible.

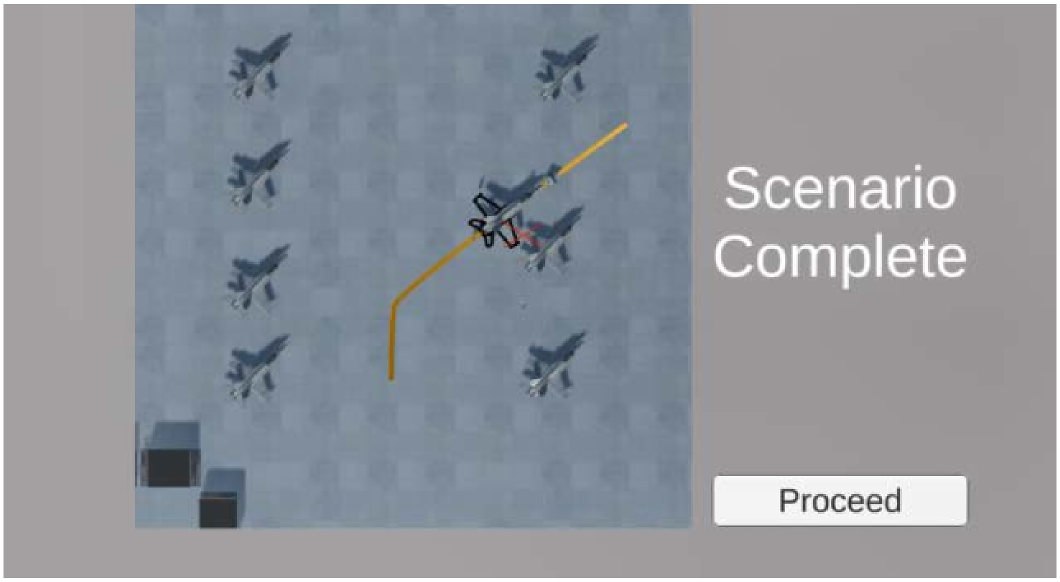


Figure 41. Aircraft Collision

We designed the scenario complete screen around the premise of providing feedback to the subject as they experience ATEAR. It is very likely that some subjects have never utilized VR before so we recognized that it could take some time for them to get used to the system and become acquainted with the perception of depth in the VR HMD.

(v) Data Output

A CSV file was outputted after each scenario set was completed. The following information was included in each CSV: subject ID, AR status, speed control status, environment type, and scenario type, start scenario time, tractor speed every 0.5 seconds, stop tractor triggered, intended end time of scenario, confidence question type and response, and/or aircraft collision triggered. Because the tractor speed was logged every 0.5 second, each scenario set produced a CSV file of about 800 lines. To simplify data analysis, we wrote a python program to extract the desired data (see Appendix C. Data Analysis Python Code). After placing each scenario set CSV file completed by a subject into one folder, this code parses through each file and places specific data in chronological order for each individual scenario. The simplified data output includes the following: subject ID, AR status, ability to control tractor speed, type of environment, type of scenario, distance (if “Hit” scenario), collision prediction (correct/incorrect), mean tow tractor speed (if speed control turned on), tow tractor speed standard deviation (if tractor speed turned on), tow tractor last known speed (if tractor speed turned on), type of confidence question, and subject’s confidence question response. Refer to Appendix D. Data Analysis Code Output for an excerpt of the output that encompasses data from one subject’s execution of all 20 scenarios.

3. Summary

This chapter discussed the design and development process of the first iteration of the ATEAR system. This process, from a conceptual design to a functioning software, took the research team and the MOVES FutureTech team roughly four months. The next step was to design the experiment and conduct a pilot study to ensure the data gleaned from ATEAR would meet our research objective.

IV. DESIGN OF EXPERIMENT

This chapter discusses the experimental design and methodology of the experiment. The sections of this chapter discuss the intended subject pool, the study design, data sets to be collected from the experiment, and the methodology of the experiment.

A. SUBJECTS

The intended audience to conduct the ATEAR experiment would be USN and USMC personnel who had, at one time or another, held a tow crew director qualification for towing F/A-18 aircraft. This subject pool would encompass not only junior Marines and Sailors who are actively responsible for towing aircraft on a daily basis, but also those senior enlisted personnel who have over a decade of experience in the field. The desired sample size of participants was between 15-40 subjects in order to obtain statistically significant results from the study. We chose these individuals as our testing audience because they have experience serving in the role for which the ATEAR system was designed. We felt that their performance and general feedback of the AR system would justify utilization of AR as a potential solution to decreasing towing-related AGMs.

B. STUDY DESIGN

1. Physical Environment

The intended physical environment for the experiment was inside of the host squadron’s ready room. The ready room is a location that exists in each squadron’s hangar that serves as a relatively quiet area uses for meetings and training. Ready rooms are not standardized, but in general, remain the same. Most ready rooms consist of one or two desks, a computer, multiple white boards, and about 20-30 seats and desks. The intended physical study environment consisted of the study participant (wearing Oculus Rift HMD) sitting in front of the laptop computer, and the proctor sitting right next to the participant (see Figure 42).

Figure 42. Subject Physical Environment

2. Experimental Conditions

We developed a counterbalanced, paired design in which each subject would complete 20 towing scenarios using ATEAR. Each subject would be assigned a subject ID at the beginning of the experiment that represented the subject for data analysis purposes. Each subject would complete two VR sessions comprised of ten scenarios for each session (see Table 5).

Table 5. Counterbalanced Experimental Design

	Odd Subject ID	Even Subject ID
Scenario Set 1	AR View	Standard View
Scenario Set 2	AR View w/ Speed Control	Standard View w/ Speed Control
Scenario Set 3	Standard View	AR View
Scenario Set 4	Standard View w/ Speed Control	AR View w/ Speed Control

C. METHODOLOGY

The focal point of the study was immersing each subject in VE using the Oculus Rift HMD discussed in Chapter III.A.1 and measuring their performance. The experiment from start to end, including surveys and other tests, was expected to take about 70 minutes. All surveys discussed below were loaded into QualtricsXM data collection platform to allow subjects to answer each question digitally (QualtricsXM, n.d.). QualtricsXM also allows responses to be exported into a CSV for offline data analysis. Another benefit of using this software was that surveys could be customized to jump to specific questions based off of a recorded response. All QualtricsXM surveys would be completed on the proctor's computer (i.e., separate computer than the computer used for ATEAR). The flow of the experiment along with the data collected at each stage are outlined below. Where relevant, the purpose for the activity also is described.

1. Pre-experiment

Each subject would complete the approved NPS institutional review board (IRB) consent form (see Appendix G. ATEAR Experiment Consent Form). Once the consent form was completed, a subject ID number would be assigned to the subject as discussed in Chapter IV.B.2. After a subject ID was assigned, the subject would answer both the demographic survey (see Appendix H. ATEAR Demographic Survey) and the pre-experiment SSQ (see Appendix I. ATEAR SSQ) on the QualtricsXM website. The demographic survey would be used to document each subject's gender, age, eye sight, aircraft towing experience, and other related information. The SSQ was a digital version of the standard paper and pencil SSQ (Kennedy et al., 1993; Curry et al., 2019) The pre-experiment SSQ would serve as a baseline measurement for the subject's level of simulation sickness. This process was projected to take about 10 minutes to complete.

2. Virtual Environment Training

After all pre-experiment surveys were completed, the subject would place the HMD on their head. The proctor would help the subjects properly fit the HMD to their head and adjust the interpupillary distance on the HMD as appropriate. Once the HMD was properly fitted to the subject, they would complete the tutorial discussed in Chapter III.B.2.d(ii).

The tutorial enabled the subject to become comfortable with navigating through, and interacting with, the VE using the same interaction modalities that would be necessary to complete the main study. The tutorial used towing environment one, where the subject practiced walking around the aircraft, was introduced to how the AR system worked, and also learned how to control the speed of the aircraft. Throughout the duration of the tutorial, the proctor would guide the subject through the ATEAR system in order to point out specific things that were not immediately obvious to the subject. To ensure each subject received the same instruction, the proctor would read the experiment script found in Appendix E. Pilot Testing Experiment Script. The tutorial process was projected to take about 10 minutes to complete.

3. Main Experiment Scenario Sets 1 and 2

Once the subject had completed the tutorial, they would be asked if they had any questions. Once all, if any, outstanding questions were answered by the proctor, the subject would begin scenario set one in accordance with Table 4. As mentioned in Chapter III.B.2.d(v)Data Output, ATEAR recorded data for each subject in four separate CSV files; each file corresponded to one scenario set. The main performance variables captured by each CSV included: subject ID, AR status, speed control status, environment type, and scenario type, start scenario time, tractor speed every 0.5 seconds, stop tractor triggered, intended end time of scenario, confidence question type and response, and/or aircraft collision triggered. As discussed in Chapter III.B.2.b(iii), subjects would answer one of two confidence questions based off actions they took during each scenario.

After the completion of scenario set one, the subject would complete scenario set two with the ability to control the speed of the tow tractor. The first two sets of scenarios were projected to take subjects about 15 minutes to complete. At the conclusion of scenario set two, each subject would remove the HMD to take a break from the VE. We implemented this VE break period because cybersickness becomes more prevalent over longer periods of exposure in VR. During this time, the subject would complete a contrast sensitivity test and a cognitive processing speed test.

a. Contrast Sensitivity Test

(i) Purpose

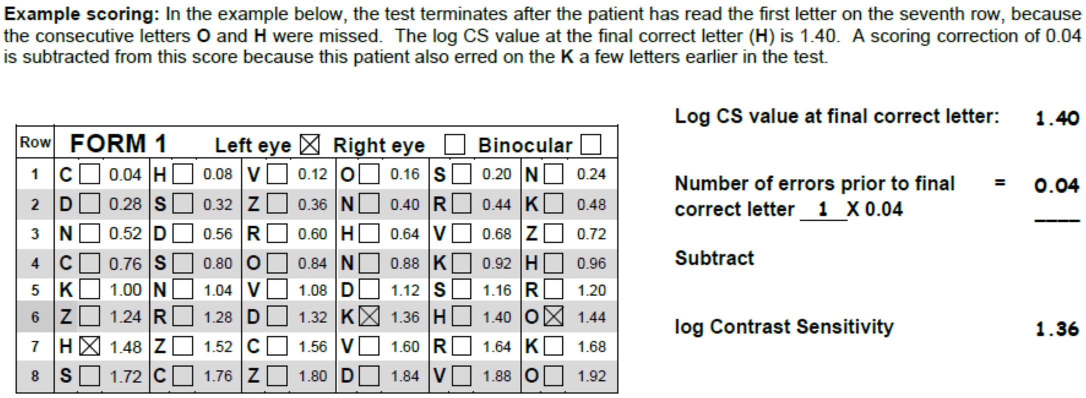
Contrast sensitivity essentially is the ability to distinguish between varying shades of gray (see Figure 43). Aircraft maintenance personnel experience various shades of gray color while executing their normal duties. When moving aircraft specifically, one's ability to properly distinguish between different contrasts of gray color can be the difference between successfully executing a towing evolution or accidentally towing the aircraft into a surrounding object. Contrast sensitivity is not only important for the real world task of towing aircraft. Because we are using VR to simulate AR and study its effects, the subject's perception of the aircraft and other objects in the VE would be paramount in identifying potential collisions and validating the fidelity of the aircraft towing process. "When the contrast between and object and the background is reduced, the quality of visual performance is reduced. This effect is more pronounced in individuals with poor vision including wearers of corrective lenses" (Mohammed, 2017, para. 4). Thus, we could ascertain if poor ATEAR performance was due to poor contrast sensitivity rather than the fidelity of the VE.

(ii) Execution and Record of Performance

There are several different types of contrast sensitivity tests. However, we selected the Mars Contrast Sensitivity test due to its popularity and ease of use (Mars Perceptrix Corporation, 2013). This test involves the use of a standardized letter chart, which consists of nine lines of specific letters. The top left letter is black. As one views the chart from top left to bottom right, each subsequent letter is a lighter shade of gray (see Figure 43).

Figure 43. Mars Contrast Sensitivity Chart. Source: Mars Perceptrix Corporation (n.d.).

The general procedure for conducting a contrast sensitivity test is very similar to that of a normal eye test. The subject is asked to cover their right eye and to read letters from left to right for each line of the chart. Once their performance with their left eye is recorded, the subject will cover their left eye and repeat the test. Unlike the standard eye exam where the subject would view the chart from approximately 10 feet away, the contrast sensitivity test is conducted with the chart only 20 inches from the subject. The scoring for each subject would be conducted in accordance with the Mars Letter Contrast Sensitivity Test Score Sheet (see Figure 44). Data collected from the contrast sensitivity test would be recorded on the proctor's computer.



Example scoring: In the example below, the test terminates after the patient has read the first letter on the seventh row, because the consecutive letters **O** and **H** were missed. The log CS value at the final correct letter (**H**) is 1.40. A scoring correction of 0.04 is subtracted from this score because this patient also erred on the **K** a few letters earlier in the test.

Row	FORM 1		Left eye ☒	Right eye ☐	Binocular ☐	
1	C ☐ 0.04	H ☐ 0.08	V ☐ 0.12	O ☐ 0.16	S ☐ 0.20	N ☐ 0.24
2	D ☐ 0.28	S ☐ 0.32	Z ☐ 0.36	N ☐ 0.40	R ☐ 0.44	K ☐ 0.48
3	N ☐ 0.52	D ☐ 0.56	R ☐ 0.60	H ☐ 0.64	V ☐ 0.68	Z ☐ 0.72
4	C ☐ 0.76	S ☐ 0.80	O ☐ 0.84	N ☐ 0.88	K ☐ 0.92	H ☐ 0.96
5	K ☐ 1.00	N ☐ 1.04	V ☐ 1.08	D ☐ 1.12	S ☐ 1.16	R ☐ 1.20
6	Z ☐ 1.24	R ☐ 1.28	D ☐ 1.32	K ☒ 1.36	H ☐ 1.40	O ☒ 1.44
7	H ☒ 1.48	Z ☐ 1.52	C ☐ 1.56	V ☐ 1.60	R ☐ 1.64	K ☐ 1.68
8	S ☐ 1.72	C ☐ 1.76	Z ☐ 1.80	D ☐ 1.84	V ☐ 1.88	O ☐ 1.92

Log CS value at final correct letter: **1.40**

Number of errors prior to final correct letter 1 X 0.04 **= 0.04**

Subtract

log Contrast Sensitivity **1.36**

Figure 44. Mars Contrast Sensitivity Scoring Example. Source: Mars Perceptrix Corporation (2013).

When analyzing results from the contrast sensitivity test, the chart referenced in Figure 45 is utilized.

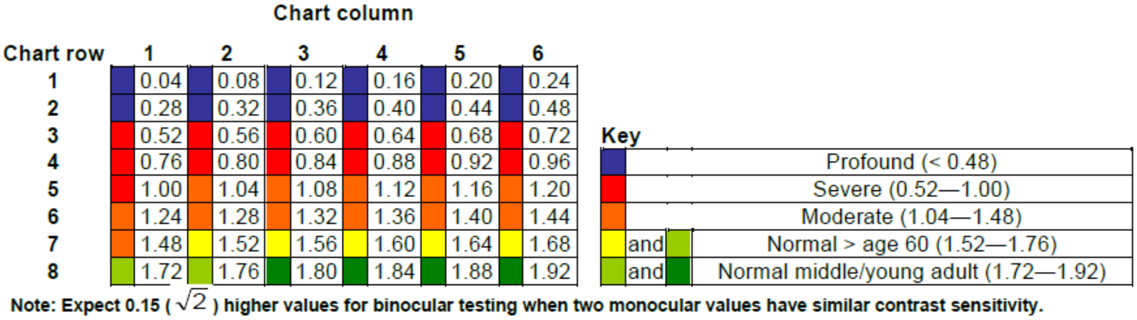


Chart column

Chart row	**1**	**2**	**3**	**4**	**5**	**6**
1	🟦 0.04	🟦 0.08	🟦 0.12	🟦 0.16	🟦 0.20	🟦 0.24
2	🟦 0.28	🟦 0.32	🟦 0.36	🟦 0.40	🟦 0.44	🟦 0.48
3	🟥 0.52	🟥 0.56	🟥 0.60	🟥 0.64	🟥 0.68	🟥 0.72
4	🟥 0.76	🟥 0.80	🟥 0.84	🟥 0.88	🟥 0.92	🟥 0.96
5	🟥 1.00	🟧 1.04	🟧 1.08	🟧 1.12	🟧 1.16	🟧 1.20
6	🟧 1.24	🟧 1.28	🟧 1.32	🟧 1.36	🟧 1.40	🟧 1.44
7	🟧 1.48	🟨 1.52	🟨 1.56	🟨 1.60	🟨 1.64	🟨 1.68
8	🟩 1.72	🟩 1.76	🟩 1.80	🟩 1.84	🟩 1.88	🟩 1.92

Key

🟦			Profound (< 0.48)
🟥			Severe (0.52—1.00)
🟧			Moderate (1.04—1.48)
🟨	and	🟩	Normal > age 60 (1.52—1.76)
🟩	and	🟩	Normal middle/young adult (1.72—1.92)

Note: Expect 0.15 ($\sqrt{2}$) higher values for binocular testing when two monocular values have similar contrast sensitivity.

Figure 45. Mars Contrast Sensitivity Scoring Thresholds. Source: Mars Perceptrix Corporation (2013).

b. Cognitive Processing Speed Test

(i) Purpose

A second factor that could impact how well a tow director detects a potential collision is cognitive processing speed; (i.e., how fast their brain works). People with relatively slow processing speed may not detect a collision in time. Therefore, after completing the contrast sensitivity test, subjects would complete a cognitive processing speed test called the trail making test (TMT) parts A and B (Bowie & Harvey, 2006). Poor performance on this test could explain poor performance in ATEAR.

(ii) Test Design and Implementation

The cognitive processing speed test would be a Unity-based version of the TMT. This version is an executable file that would be completed by each subject using a Microsoft Surface tablet, by using the touch screen and their preferred left or right hand index finger. The test was composed of four modules: tutorial of Trail A, Trail A test, tutorial of Trail B, Trail B test. The home screen for the cognitive processing speed test can be seen in Figure 46.

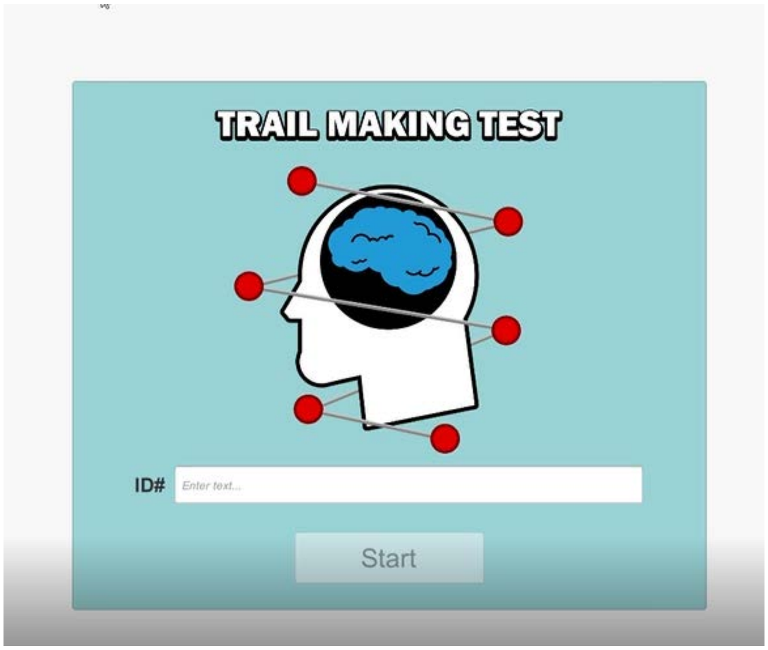


Figure 46. Unity-based TMT Home Screen

Once the subject’s ID was entered, the tutorial for Trail A would load (see Figure 47).

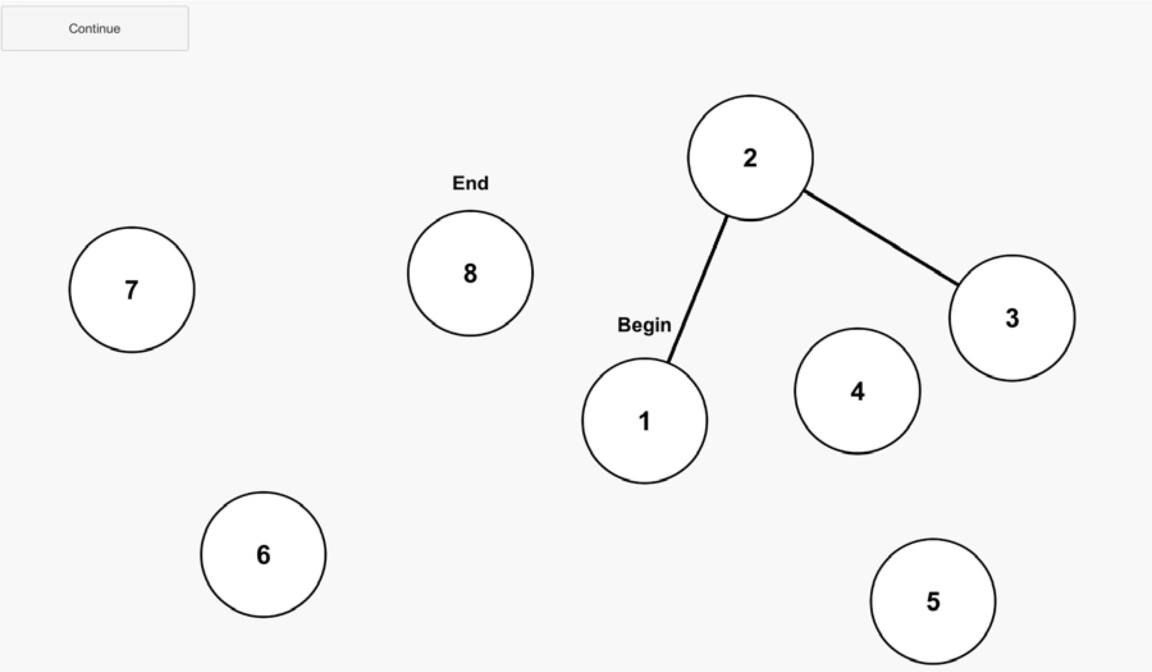


Figure 47. Unity-based TMT Trail A Tutorial

- **Tutorial of Trail A –** the black line connecting circles (1) and (2) and circles (2) and (3) in Figure 47 – is drawn by the program to show the subject what they need to do. In this tutorial, the subject would begin at the point the line left off, in this case circle (3). Using their finger, the subject would connect circle (3) to circle (4) and so on; each circle was to be connected in sequential order.

- **Trail A Test** – after completing the tutorial, the subject would click "Start Test" to officially start the Trail A test. Unlike the tutorial that consisted of only eight numbers, the official test included numbers up to 25 (see Figure 48).

- **Trail B Tutorial –** this tutorial was similar to that of the Trail A tutorial. However, numbers and corresponding letters from the alphabet were to be linked in sequential order. For example, the correct order would be circles (1), (A), (2), (B), (3), (D) and so on.

- **Trail B Test** – similar to the Trail A test, the Trail B test contains more numbers and letters than its tutorial.

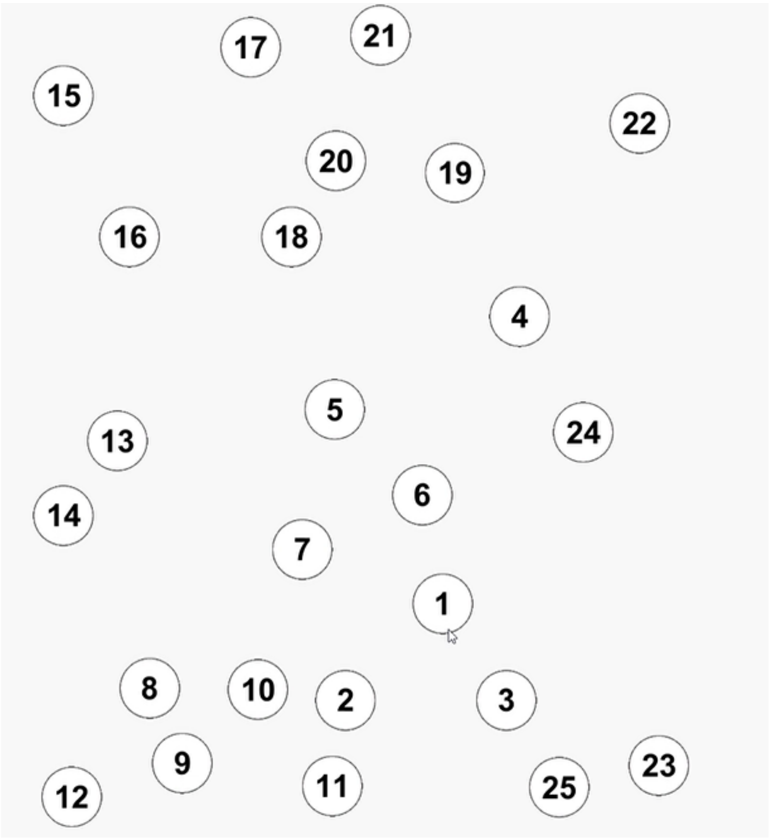


Figure 48. Unity-based Trail A Test

For each module, subjects would drag their finger to connect the circles in sequential order. In instances where the subject accidentally selected the wrong circle, the background of the screen would flash red (see Figure 49). Within a second, the red background would return to the standard white background and the most recent, correct circle, would flash green (see Figure 50). This would remind the subject of their most recent correct circle, as well as serve as the location to resume the test.

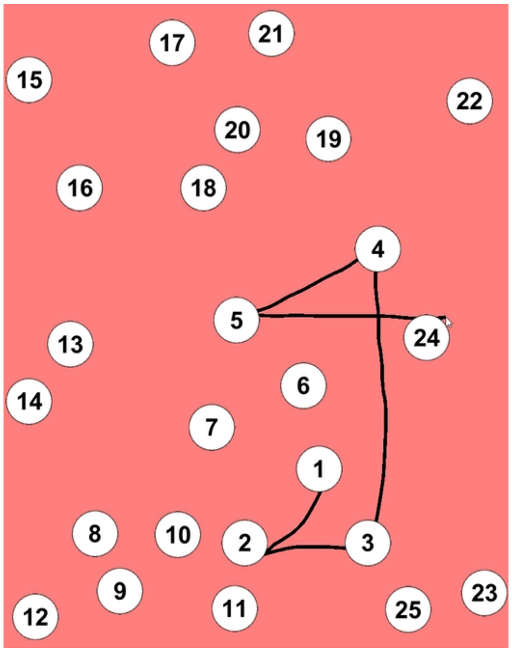


Figure 49. Unity-based TMT Incorrect Trace Warning

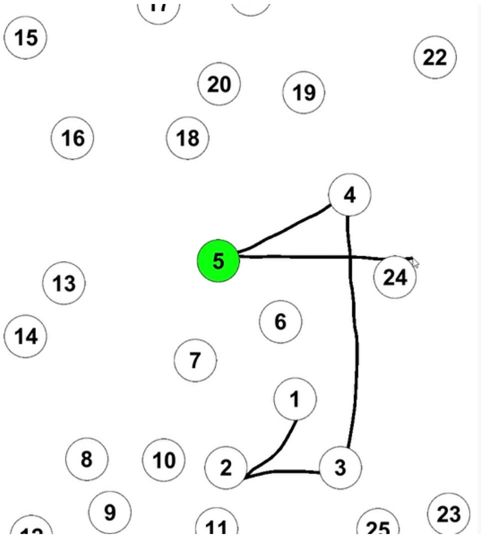
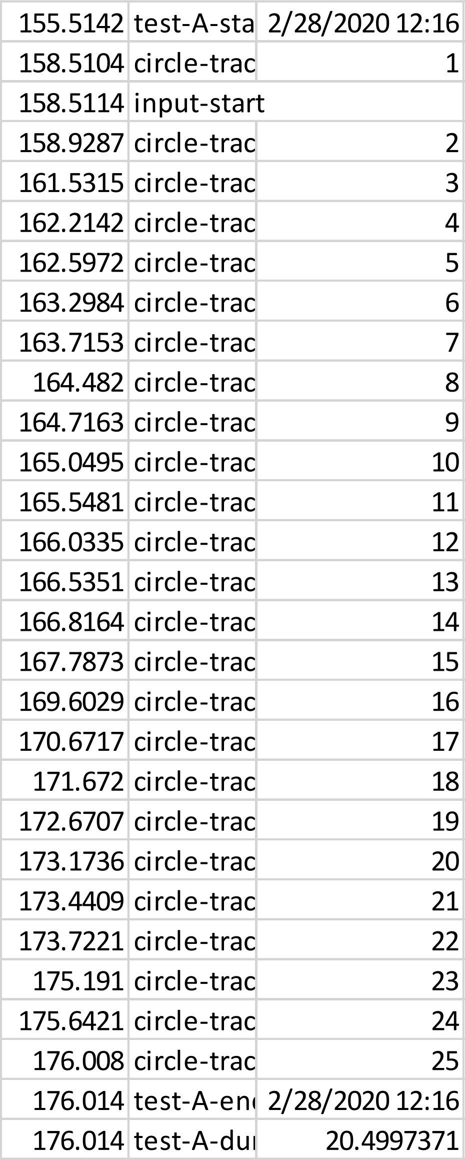


Figure 50. Unity-based TMT Most Recent Correct Circle Shown After Trace Error

(iii) Test Output

The Unity-based version of the TMT logged the following results into a single CSV for each subject: subject ID, start time, simulation time each circle was correctly traced, simulation time each trace error occurred, the end of test time, and the duration of the test (see Figure 51). The primary variable of interest for both Trails A and B tests is the total completion time (Bowie & Harvey, 2006). Typical performance times, or expectations, based on age and education can be found in Figure 52. Data collected from the TMT would be recorded on the proctor's computer.



155.5142	test-A-sta	2/28/2020 12:16
158.5104	circle-trac	1
158.5114	input-start	
158.9287	circle-trac	2
161.5315	circle-trac	3
162.2142	circle-trac	4
162.5972	circle-trac	5
163.2984	circle-trac	6
163.7153	circle-trac	7
164.482	circle-trac	8
164.7163	circle-trac	9
165.0495	circle-trac	10
165.5481	circle-trac	11
166.0335	circle-trac	12
166.5351	circle-trac	13
166.8164	circle-trac	14
167.7873	circle-trac	15
169.6029	circle-trac	16
170.6717	circle-trac	17
171.672	circle-trac	18
172.6707	circle-trac	19
173.1736	circle-trac	20
173.4409	circle-trac	21
173.7221	circle-trac	22
175.191	circle-trac	23
175.6421	circle-trac	24
176.008	circle-trac	25
176.014	test-A-en	2/28/2020 12:16
176.014	test-A-du	20.4997371

Figure 51. Unity-based TMT Trail A Output Example

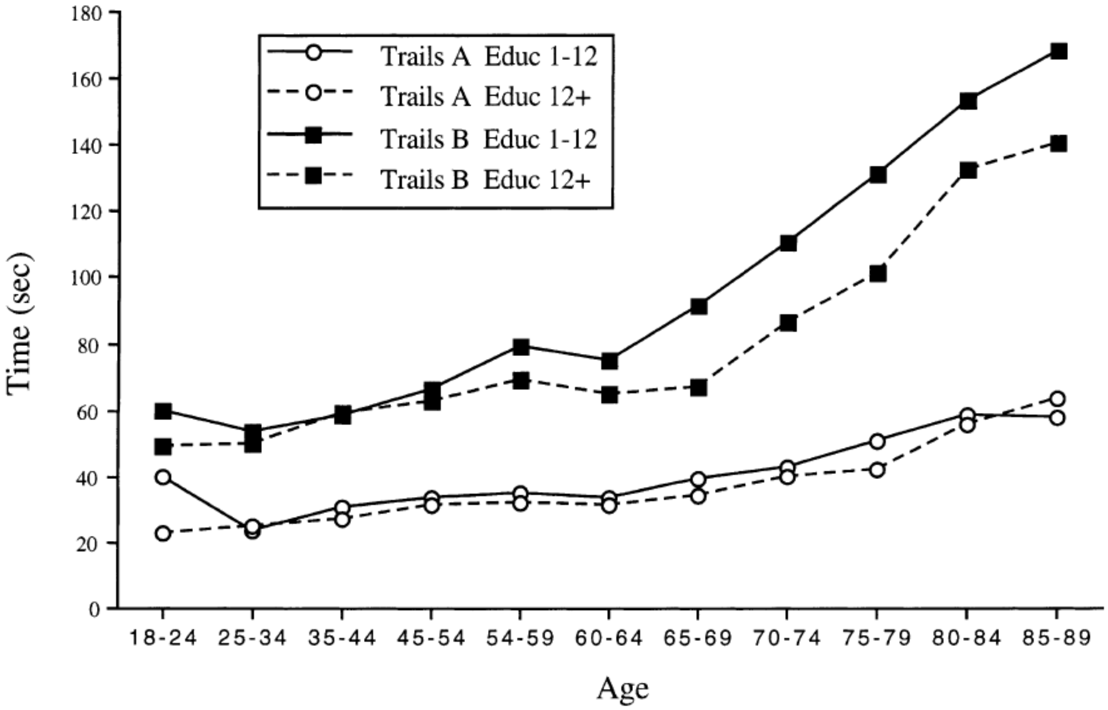


Figure 52. Typical Scoring on TMT Parts A and B Based on Age and Education. Source: Tombaugh (2004).

4. Main Experiment Scenario Sets 3 and 4

Once the cognitive processing speed test was complete, the subject would remount the HMD on their head. After any outstanding questions were answered by the proctor, the subject would complete scenarios sets three and four in accordance with the scenario set layout based off their subject ID (see Table 5). The main performance measures collected for scenario sets three and four were exactly the same as scenario sets one and two. The projected completion time for the remaining two sets of scenarios was about 15 minutes.

5. Post-experiment

Once the subject completed the remaining sets of scenarios, they would complete the post-experiment SSQ on the QualtricsXM website (see Appendix I. ATEAR SSQ). The results from this SSQ would be compared from the pre-experiment SSQ collected at the beginning of the experiment, to ensure the subject was not experiencing any significant effects of cybersickness that could prevent them from returning to work. After completing the post-experiment SSQ, the subject would complete the post-experiment survey (see Appendix J. ATEAR Post-experiment Survey). The variables of interest from this survey included: the subject’s ability to experience towing the towing scenarios in the VE with visual clarity, if they opted to wear corrective lenses of any kind during the experiment, the accuracy of modeling the towing of an F/A-18, whether they had enough time to make decisions in the VE, the usability and impact of using the AR system, as well as their expert opinion regarding the potential fleetwide implementation of a similar AR system. This process was projected to take about 10 minutes to complete. Also, the completion of the post-experiment survey and a debrief would mark the conclusion of the experiment.

D. SUMMARY

This chapter discussed the design of the experiment, as well as the methodology of how the experiment would be conducted. This chapter also spoke to the methods of data collection for each subject, as well as how data would be utilized to answer the research questions posed in this thesis.

V. PILOT TESTING RESULTS AND ANALYSIS

Due to unforeseen circumstances surrounding the 2020 COVID-19 pandemic, travel restrictions were placed on DoD personnel on March 13th, 2020. Although the NPS IRB approved the experiment protocol (NPS.2020.0019-IR-EP7-A), after consulting NPS leadership, we determined that conducting the experiment with active duty personnel could potentially cause unnecessary harm to members of the research team, as well as participants of the experiment. Fortunately, we had completed pilot testing that yielded eight volunteer practice subjects. Because we were unable to officially conduct the experiment, we received approval from the NPS IRB to include the results from our pilot testing in this thesis (NPS.2020.0019-AM01-EP7-A). All pilot study participants authorized the analysis of their pilot study data by complting an additional consent form (see Appendix F. ATEAR Pilot Testing Consent Form).

This chapter discusses results from pilot testing. The methodology used in pilot testing was the same methodology in the originally approved IRB package, except that we were unable to acquire the contrast sensitivity chart in time to conduct the pilot testing. This section also includes lessons learned from executing the pilot testing and conducting analysis of the data collected from it. During pilot testing, pilot1's performance data from ATEAR was compromised due to an error made by the proctor of the experiment. As a result, the only data collected from pilot1 and analyzed in this paper was the survey data (demographic, SSQ, and post-experiment survey). The software tools utilized for the statistical analysis of the collected data were JMP Pro Version 11 and Microsoft Excel. Also, due to the small sample size from the pilot testing participants, only descriptive statistics were utilized for analysis.

The pilot testing shed some light on several issues with ATEAR that needed to be changed before officially conducting the experiment. Therefore, this chapter will also discuss changes to ATEAR that were implemented into version 2 of ATEAR after the pilot testing was completed. In addition to the changes already incorporated in version 2 of ATEAR, other changes will be addressed to resolve issues that became apparent during the analysis of the pilot testing results.

A. RESULTS

1. Demographic Survey Data

The information discussed in this section is depicted in Appendix K. Demographic Survey Results. Our pilot testing had a total of eight participants, six Marine officers, one Army officer, and one civilian. Two of the eight participants were female and six were male. All participants were right-handed. The average age of pilot participants was 32.4 years old and the average time in service (years spent in the military) was 8.8 years. Of the seven military officers who participated, the following list depicts their area of specialty:

- (3) Logistics
- (1) Infantry
- (1) Defense Air Control
- (1) Artillery
- (1) Army Modeling and Simulation Officer

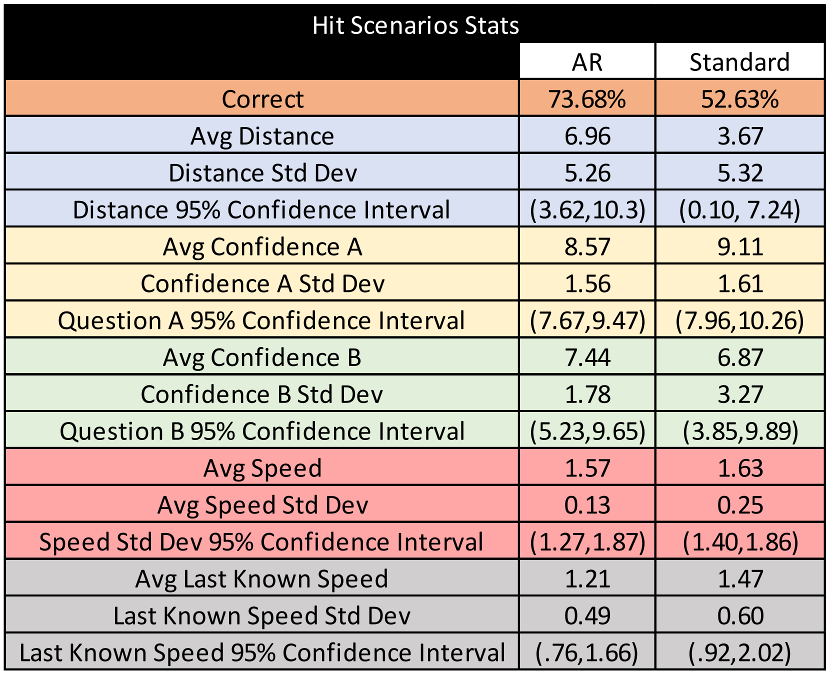
Of the eight participants, only one, pilot5, required corrective lenses. For the experiment, this subject chose to wear their glasses. Seven of the eight participants had experience using VR displays. Regarding Q23, 62.5 percent of the participants played computer games weekly for one to two hours, 12.5 percent played computers games weekly for three to four hours, and 25 percent did not play computer games at all on a weekly basis. Every participant marked “No” for Q24 regarding their susceptibility to motion sickness. Over half of the questions presented in the demographic survey were tailored to enlisted USN and USMC aircraft maintenance personnel. Because the participants in the pilot study had no experience in aircraft maintenance, they provided superficial answers to the following questions referenced in Appendix H. ATEAR Demographic Survey: Q25, Q10, Q12, Q14, Q15, Q17, Q18, Q19, and Q20. Because of this, these questions were not analyzed.

2. Addressing Hypotheses

As discussed earlier, the limited sample size prevented us from using inferential statistics to properly test our hypotheses. The exclusion of performance data from pilot1 left us with a sample size of seven for performance analytics. Therefore, there was no formal testing of each hypothesis. However, we were able to use descriptive statistics to gain some insight regarding pilot participants' ATEAR performance. Because each environment had "Hit," "Danger," "Caution," and "Miss" variants, we blocked the data by environment number and type. Refer to Appendix M. Performance Data Blocked by Environment Number and Type for each subject's performance on each environment.

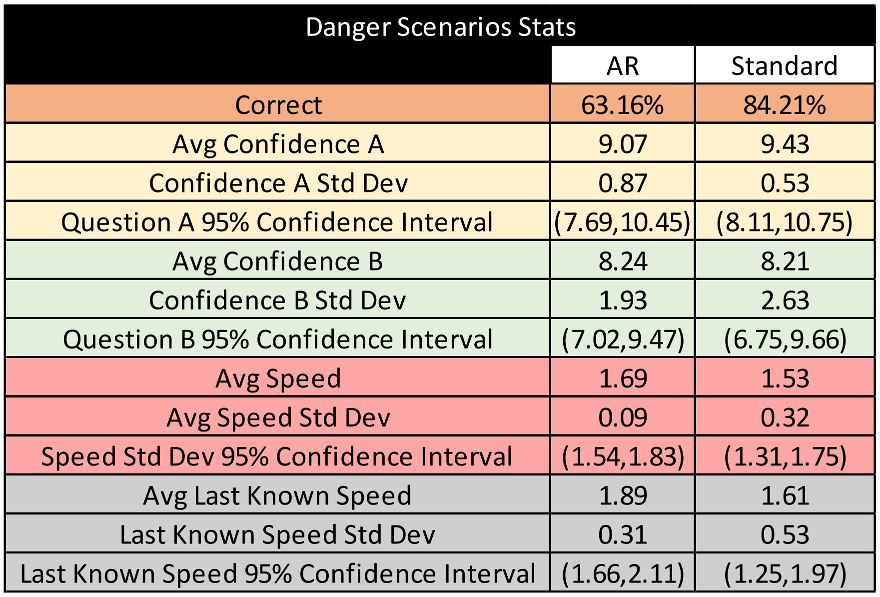
This section will commonly reference the summary statistics of "Hit" and "Danger" scenarios depicted Table 6 and Table 7. Data for these tables was derived from each "Hit" scenario (see Appendix N. Hit Scenario Analytics) and each "Danger" scenario (see Appendix O. Danger Scenario Analytics). Note that pilot6's data was manually corrected in Appendix O. Danger Scenario Analytics. The correct identification value was utilized in the supporting analysis for the first and third hypotheses. However, because the subject completed the incorrect confidence question for this scenario, the confidence question results were excluded from analysis. This issue will be discussed further in Chapter V.B.2.c. Because performance regarding the collision identification between the AR and standard views both had a prediction rate of 100 percent for "Caution" and "Miss" scenarios, we opted to not analyze performance in those scenarios. The issues with these types of scenarios will be addressed in Chapter V.B.1.

Table 6. “Hit” Scenario Summary Statistics



Hit Scenarios Stats	AR	Standard
Correct	73.68%	52.63%
Avg Distance	6.96	3.67
Distance Std Dev	5.26	5.32
Distance 95% Confidence Interval	(3.62,10.3)	(0.10, 7.24)
Avg Confidence A	8.57	9.11
Confidence A Std Dev	1.56	1.61
Question A 95% Confidence Interval	(7.67,9.47)	(7.96,10.26)
Avg Confidence B	7.44	6.87
Confidence B Std Dev	1.78	3.27
Question B 95% Confidence Interval	(5.23,9.65)	(3.85,9.89)
Avg Speed	1.57	1.63
Avg Speed Std Dev	0.13	0.25
Speed Std Dev 95% Confidence Interval	(1.27,1.87)	(1.40,1.86)
Avg Last Known Speed	1.21	1.47
Last Known Speed Std Dev	0.49	0.60
Last Known Speed 95% Confidence Interval	(.76,1.66)	(.92,2.02)

Table 7. “Danger” Scenario Summary Statistics



Danger Scenarios Stats	AR	Standard
Correct	63.16%	84.21%
Avg Confidence A	9.07	9.43
Confidence A Std Dev	0.87	0.53
Question A 95% Confidence Interval	(7.69,10.45)	(8.11,10.75)
Avg Confidence B	8.24	8.21
Confidence B Std Dev	1.93	2.63
Question B 95% Confidence Interval	(7.02,9.47)	(6.75,9.66)
Avg Speed	1.69	1.53
Avg Speed Std Dev	0.09	0.32
Speed Std Dev 95% Confidence Interval	(1.54,1.83)	(1.31,1.75)
Avg Last Known Speed	1.89	1.61
Last Known Speed Std Dev	0.31	0.53
Last Known Speed 95% Confidence Interval	(1.66,2.11)	(1.25,1.97)

a. Hypothesis 1 – Collision Detection Rate

For the “Hit” scenarios, the AR system proved to be more effective overall with regard to properly identifying if a collision was about to occur. Collisions were properly identified 74 percent of the time using the AR system versus 53 percent of the time using the standard view. Despite performing well with "Hit" scenarios, the collision identification using the AR system proved to be less accurate than the standard view when predicting if a collision was going to occur; 63.16 percent and 84.21 percent, respectively. At first glance, one would assume this is a negative implication of using the AR system. However, the 63.16 figure tells us that 36.84 percent of the time, subjects chose to blow the whistle because they felt that a collision was going to occur. When applying this action in a real-world towing evolution, preemptively blowing a whistle due to the perceived possibility of a collision would be the most desirable action maintenance leadership. The goal is to avoid collisions at all costs.

b. Hypothesis 2 - Mean Stopping Distance

On average, subjects stopped the aircraft 6.96 units away from the scheduled collision point using the AR view and only 3.67 units using the standard view. Those who used the AR view stopped the aircraft 3.29 units ahead those with the standard view. In other words, the AR system nearly doubled a subject's ability to determine a collision was going to happen and stop the towing evolution. The standard deviation for the AR view and the standard view were similar, 5.26 and 5.32. After calculating a 95 percent confidence interval for AR and standard view distances, we see that the lower confidence limit for the standard view is nearly zero at 0.10, which is a point of concern. Despite these promising results, this data is only representative of 29 of the intended sample size of 35 for "Hit" scenarios; one out of five "Hit" scenarios per environment multiplied by the seven subjects). As depicted in Appendix M. Performance Data Blocked by Environment Number and Type, six data points have a "*" in place of the distance figure due to insufficient data. This will be discussed in Chapter V.B.2.b.

c. Hypothesis 3 – Confidence Levels

As a reminder, subjects completed question A if they blew their whistle, and question B for all other instances.

(i) ATEAR Confidence Question A

For “Hit” scenarios, question A yielded a lower average confidence score when using the AR view when compared to the standard view by 0.54. Additionally, the standard deviation for responses for both AR and standard views were within .05 of each other, indicating similar levels of variability in pilot participants’ responses. The 95 percent confidence intervals almost completely overlap each other, depicting negligible differences in confidence between the two conditions. Additionally, issues regarding the experiment script discussed in Chapter V.B.2.a could have impacted confidence responses when using the AR system.

Much like the “Hit Scenarios,” those using the AR view yielded a lower average of confidence scores for “Danger” scenarios. It is important to note that because this scenario did not include a collision, the sample size for question A responses is much smaller than in the “Hit” scenarios; four occurrences of question A using AR and three using the standard view. The standard deviation for both AR and standard views was almost a full point less than the deviations noted in the “Hit” scenarios, indicating more consistency in pilot participants’ experience with the “Danger” scenarios. We also note that overall, those with the standard view were more confident that a collision would occur, yet they were incorrect.

(ii) ATEAR Confidence Question B

“Hit” scenarios yielded higher confidence scores using the AR system than the standard view. Note that the subjects who answered this question for “Hit” scenarios failed to prevent the collision from happening. There were five occurrences of this question for the AR view and six for the standard view. The experiment script failing to mention distances as a driver to the AR system discussed in Chapter V.B.2.a could have contributed to the higher degree of confidence using the AR view. The standard deviation for responses from AR users remained similar to those who responded to question A, 1.78 and 1.56, respectively. However, there was much greater variability in confidence ratings for subjects who used the standard view than those using the AR view.

Average confidence ratings between the AR view and the standard view for "Danger" scenarios was almost the same, 8.24 (sd = 1.93) and 8.21 (sd = 2.63) respectively. However, we did see much more variability in confidence ratings for those who used the standard view than those who used the AR view. We conclude that for "Danger" scenarios, subjects were more consistently confident. We attribute this to the AR system enabling a higher degree of awareness.

(iii) Tow Tractor Speed Modulation

There was no substantial difference in speed modulation between AR and standard views for both "Hit" and "Danger" scenarios. The average speed for both scenario types and view conditions was around 1.53-1.69 units per second. As discussed in Chapter III.B.2.b(iii), the trigger pulled in fully on the Oculus Rift controller would yield a speed of 2.0 units per second. When subjects had the ability to control the speed using the AR view, their speed remained more consistent than their standard view counterparts in both types of scenarios. A consistent speed does suggest a higher degree of confidence in moving the aircraft using the AR view.

(iv) Post-experiment Survey

Results from the post-experiment survey can be found in Appendix L. Post-experiment Survey Data. Despite subject's using the AR view having a lower degree of confidence for "Hit" scenarios, seven of the eight subjects felt that the AR view helped their understanding of the aircraft's location in relation to other items in the scene. When asked about their overall confidence using the AR system, the average score (on a scale of 1-10) was 8.4 (sd = 1.37). Additionally, subjects felt that the AR system was easy to use; the mean ease of use score for use of the AR system (on a scale of 1-10) was 2.04 (sd = 2.38). All subjects felt that a similar AR system should be incorporated in the towing process across the fleet. Question 16 asked why subjects felt a similar AR system should be fielded to the fleet. Several of their responses are below:

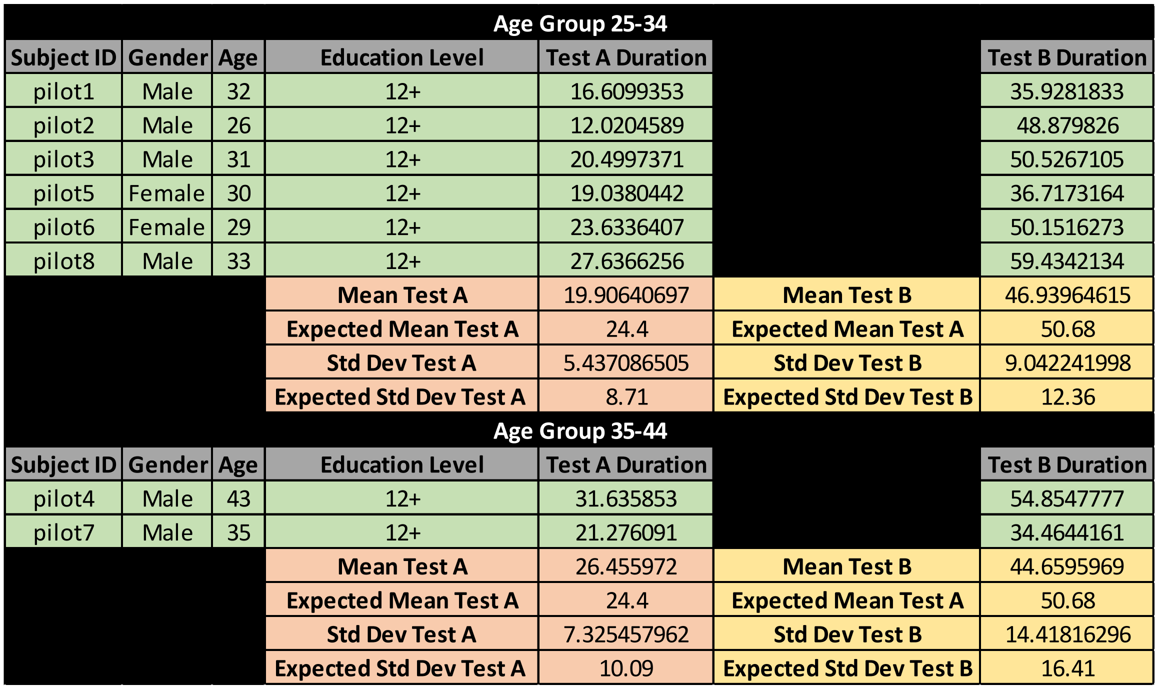
- "Increased visual accuracy/detail."
- "…it is easier to see the edges of the wings."

- “…it brought [potential impact point] to your attention and made you focus [more] on that specific area.”

3. Cognitive Processing Speed Results

The results from the Unity-based TMT discussed in Chapter IV.C.3.b are depicted in Table 8. The expected means and standard deviations for Trails A and B were derived from Dr. Tombaugh’s study regarding normative data for the Trail Making Test (Tombaugh, 2004). We see that all subjects, except pilot4 and pilot8, completed Trails A and B faster than the expected mean time. The standard deviation for both tests in both age groups was also less than the expected standard deviation for each test. However, there was significant variability for each test; 5-7 seconds for Trail A and 9-14 seconds for Trail B. In an experiment conducted with an adequate sample size, processing speed may impact how quickly people react to potential collisions. We conclude that most subjects performed within the expected norms with regard to the duration of each test and the overall variability across our sample size.

Table 8. Cognitive Processing Speed Results



Age Group 25-34						
Subject ID	Gender	Age	Education Level	Test A Duration		Test B Duration
pilot1	Male	32	12+	16.6099353		35.9281833
pilot2	Male	26	12+	12.0204589		48.879826
pilot3	Male	31	12+	20.4997371		50.5267105
pilot5	Female	30	12+	19.0380442		36.7173164
pilot6	Female	29	12+	23.6336407		50.1516273
pilot8	Male	33	12+	27.6366256		59.4342134
			Mean Test A	19.90640697	**Mean Test B**	46.93964615
			Expected Mean Test A	24.4	**Expected Mean Test A**	50.68
			Std Dev Test A	5.437086505	**Std Dev Test B**	9.042241998
			Expected Std Dev Test A	8.71	**Expected Std Dev Test B**	12.36
Age Group 35-44						
Subject ID	Gender	Age	Education Level	Test A Duration		Test B Duration
pilot4	Male	43	12+	31.635853		54.8547777
pilot7	Male	35	12+	21.276091		34.4644161
			Mean Test A	26.455972	**Mean Test B**	44.6595969
			Expected Mean Test A	24.4	**Expected Mean Test A**	50.68
			Std Dev Test A	7.325457962	**Std Dev Test B**	14.41816296
			Expected Std Dev Test A	10.09	**Expected Std Dev Test B**	16.41

4. SSQ DATA

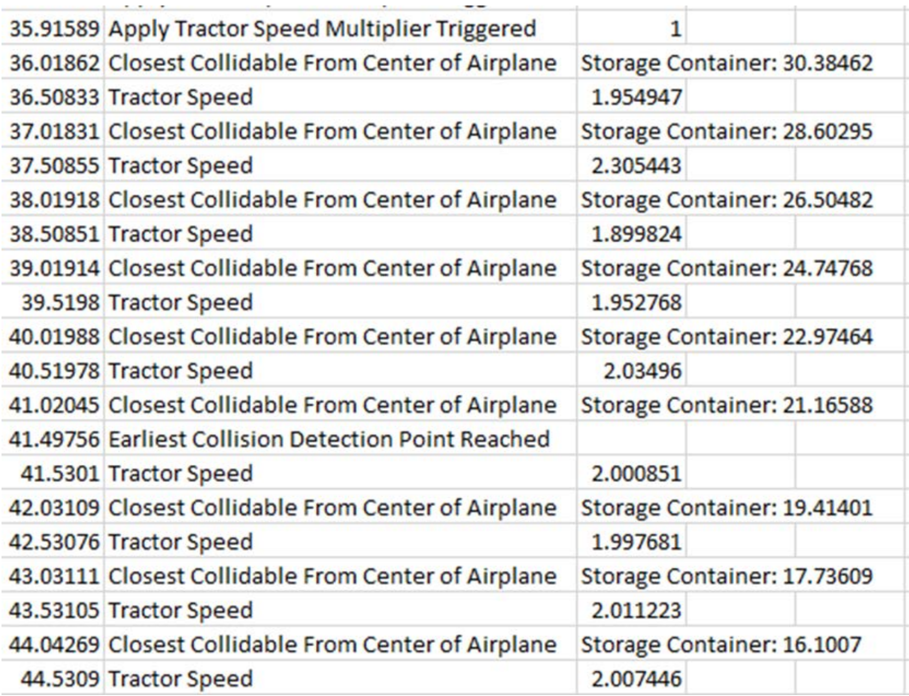
As reminder, subjects comepleted an SSQ at the beginning of the experiment and another immediately following the conclusion of the experiment. The scores of for each subject with regard to their nausea (N), oculomotor (O), disorientation (D), and total score (TS) are depicted in Appendix P. SSQ Results. There were no significant changes from before and after VR exposure when looking at the data in each category. We compared the TS of before and the TS after, which yielded a mean difference in SSQ total score of 16.013 (sd = 59.80, 95% C.I.: (-33.98,65.91)). A negative TS score would indicate that the subject reported a higher SSQ score prior to VR exposure than after. Because 0.00 was included in our TS SSQ confidence interval, we conclude that the experiment did not lead to VR-related sickness.

B. ATEAR VERSION 2

1. Pilot Testing Changes Already Implemented

a. Distance Metric Included for Non-Hit Scenarios

Because the stopping distance metric was calculated using the programmed simulation time, whistle blown time, and the last known speed of the tow tractor, it was impossible to determine a stopping distance metric for non-hit scenarios. When looking at the data output from version 1 of ATEAR, we were unable assert any information from non-hit scenarios. As 15 of the 20 scenarios were “Danger,” “Caution,” or “Miss” scenarios, only five scenarios provided useful data. To resolve this issue, we modified the output of ATEAR to display the distance from the center of the aircraft to the closest object to the aircraft that could result in a collision for every second (see Figure 53).



35.91589	Apply Tractor Speed Multiplier Triggered	1
36.01862	Closest Collidable From Center of Airplane	Storage Container: 30.38462
36.50833	Tractor Speed	1.954947
37.01831	Closest Collidable From Center of Airplane	Storage Container: 28.60295
37.50855	Tractor Speed	2.305443
38.01918	Closest Collidable From Center of Airplane	Storage Container: 26.50482
38.50851	Tractor Speed	1.899824
39.01914	Closest Collidable From Center of Airplane	Storage Container: 24.74768
39.5198	Tractor Speed	1.952768
40.01988	Closest Collidable From Center of Airplane	Storage Container: 22.97464
40.51978	Tractor Speed	2.03496
41.02045	Closest Collidable From Center of Airplane	Storage Container: 21.16588
41.49756	Earliest Collision Detection Point Reached	
41.5301	Tractor Speed	2.000851
42.03109	Closest Collidable From Center of Airplane	Storage Container: 19.41401
42.53076	Tractor Speed	1.997681
43.03111	Closest Collidable From Center of Airplane	Storage Container: 17.73609
43.53105	Tractor Speed	2.011223
44.04269	Closest Collidable From Center of Airplane	Storage Container: 16.1007
44.5309	Tractor Speed	2.007446

Figure 53. ATEAR Version 2 Distance Output Example

We opted to use the center of the aircraft as the distance metric instead of the distance from both port and starboard wing tips for two reasons. First, implementing a method to identify closest objects to each wing tip and calculate the respective distances would not only be computationally expensive, but would also take too much time to implement. Second, there were no instances in the scenario set that had the aircraft an equal distance from two objects of the same distance at the same time. Therefore, using the center of the aircraft for the distance metric would work for our purposes.

b. Confidence Questions

The embedded confidence questions caused some confusion with subjects during pilot testing. As a reminder the two confidence questions and respective actions that cue each question are as follows:

- Question A – When you blew the whistle, how confident were you that a collision was going to happen? (*trigger: whistle blown, regardless of programmed collision*)

- Question B - Before the scenario ended, how confident were you that the aircraft would finish its route collision free? (*trigger: whistle NOT blown, regardless of programmed collision*)

From a programming aspect, if the whistle was not blown by the subject, the trigger for ending the scene came from the programed actions in the scene (i.e., not input from the user). With regard to the embedded confidence questions, we were interested in each subject's confidence at the most stressful point of the tow (i.e., closest point of a potential collision). Some scenarios took a minute or more to complete and question B only addressed the end of the scenario. In some of these scenarios, the most stressful part of the tow, and presumably a subject's least level of confidence, occurred about halfway through the scenario rather than at the end of the scenario. As a remedy to this issue, we instituted an additional confidence question. The updated confidence questions and respective actions that cue each question are as follows:

- Question A – When you blew the whistle, how confident were you that a collision was going to happen? (*trigger: whistle blown, regardless of programmed collision*)

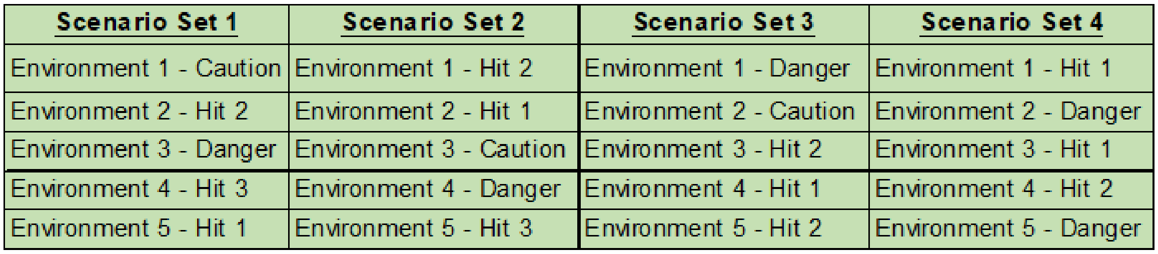
- Question B - Before the scenario ended, how confident were you that the aircraft would finish its route collision free? (*trigger: whistle NOT blown, programmed collision*)

- Question C – What was your lowest degree of confidence that the aircraft would finish its route collision free? (*trigger: whistle NOT blown, no programmed collision*)

c. Scenario Layout

Our original scenario layout consisted of only five “Hit” scenarios (i.e., one hit scenario for each environment). Even though we did have some subjects stop the aircraft from moving on some “Danger” scenarios, almost every subject scored 100 percent on the “Caution” and “Miss” scenarios. Despite adding a distance metric for non-hit scenarios, one of the driving efforts behind this project was to see if the AR system could prevent towing collisions. Therefore, we needed to ensure subjects experience more “Hit” scenarios (see Table 9). We removed “Miss” scenarios from ATEAR and added an additional “Hit” scenario for each environment. This resulted in a total of 10 “Hit” scenarios, five “Danger” scenarios, and five “Caution” scenarios.

Table 9. ATEAR Version 2 Scenario Set Break Down



Scenario Set 1	**Scenario Set 2**	**Scenario Set 3**	**Scenario Set 4**
Environment 1 - Caution	Environment 1 - Hit 2	Environment 1 - Danger	Environment 1 - Hit 1
Environment 2 - Hit 2	Environment 2 - Hit 1	Environment 2 - Caution	Environment 2 - Danger
Environment 3 - Danger	Environment 3 - Caution	Environment 3 - Hit 2	Environment 3 - Hit 1
Environment 4 - Hit 3	Environment 4 - Danger	Environment 4 - Hit 1	Environment 4 - Hit 2
Environment 5 - Hit 1	Environment 5 - Hit 3	Environment 5 - Hit 2	Environment 5 - Danger

2. Required Changes for Official Experiment

a. Scenario Script

The AR tutorial section of the experiment script used for the pilot testing stated, “If the wingtip indicator is red, DO NOT assume the aircraft will collide with the object.” The intent behind including this statement in the experiment script was to reduce dependence on the AR system by subjects. However, many subjects waited until the last second before a collision occurred before triggering a whistle blow; almost as if subjects felt like it was a game to wait as long as possible before making their decision. In the real world task, we would want tow crew members to stop the aircraft sooner rather than later when the potential for a collision to occur became apparent.

We believe the subjects knowing that a red wing tip track from the AR system would not guarantee a collision could have skewed the stopping distance data. Moving forward, we propose altering the script in a way that ties wing tip track colors to distances. For example, the experiment script should say, “A green wing tip track indicates there are no objects within six feet of the wing tip. A yellow wing tip track indicates an object is within three feet from the wingtip. A red wing tip track indicates an object is within six inches of the wing tip.”

b. Scene Playback “Proceed” Button

As discussed in Chapter 3.2.c.4, after a whistle is blown, the scenario is paused while the subject completes their confidence question. Once the subject completes the confidence question, the scenario continues to run (from the top down view) until the aircraft reaches its scheduled stopping point. During the scenario complete screen, the scenario is not being replayed to the subject. In fact, the scenario is continuing to play until it was programmed to end. For “Hit” scenarios, collisions are triggered during this time. Note that during the scenario playback, the “Proceed” button is present on the right side of the screen (see Figure 40). Several subjects from the pilot testing selected the “Proceed” button prior to the aircraft reaching the end of its programmed route. As a result, collisions were never triggered for these scenarios. Since the mean stopping distance metric is calculated using the last known tow tractor speed, whistle blown sim time, and scheduled collision time, the absence of a scheduled collision time made it impossible to gather distance data. Prior to conducting an official experiment with ATEAR, we suggest deactivating the “Proceed” button until the scene playback is complete.

c. Scheduled Collisions on Non-Hit Scenarios

As discussed in Chapter III.B.2.a(i), each towing scenario was constructed by simply changing the aircraft path of travel. Even though the aircraft starting point remained the same, the aircraft destination was changed. By slightly changing the path of travel for the aircraft, each scenario was able to be constructed in an expedient manner. For "Hit" scenarios, the distance metric for the mean stopping distance was calculated using a scheduled collision time. For all other types of scenarios, no scheduled collision time was supposed to exist. Additionally, the data analysis code depicted in Appendix C. Data Analysis Python Code utilized the scheduled collision time to determine if the subject correctly executed the scenario.

During pilot6's run through "Environment 1 – Danger," a collision was triggered by ATEAR, even though the environment was not intended to include a scheduled collision time. The subject taking no action and letting the scenario play out until completion was expected because the scenario was coded as a "Danger" scenario; yet a collision was still triggered. Likewise, on the same scenario, pilot2 also took no action. However, this time no collision was triggered. The inconsistency could be attributed to the physics incorporated in models in ATEAR. During the time the aircraft makes the turn, an increased speed could place the aircraft on a slightly different destination than an aircraft traveling at a slower speed. Unfortunately, the time in which the aircraft begins to turn is not logged. However, when comparing performance between pilot2 and pilot6 on this particular scenario, pilot2 concluded the scenario with 100 percent greater speed, a faster mean speed, and a greater deviation of speed throughout the scenario. The aircraft under pilot2's control could have traveled slower or faster during the turn in the scenario, resulting in a slightly different end location than the same aircraft under pilot6.

Table 10. Pilot2 Versus Pilot6 Performance Environment 1- Danger

Subject ID	Last Known Speed	Mean Speed	Speed Std. Dev
pilot2	1.98 unit/s	1.43 unit/s	0.51
pilot6	0.999 unit/s	1.15 unit/s	0.39

Before officially using ATEAR version two, for an experiment, “Environment 1-Danger” will need to be revisited to ensure the scenario is consistent for each user experience. In addition to “Environment 1 - Danger,” the updated “Danger” and “Caution” scenarios need to also be tested to ensure the experience for each subject remains consistent and that each scenario results in the desired outcome.

C. SUMMARY

Results from pilot testing from a small sample of volunteers suggest that the simulated AR system can increase situational awareness for towing evolutions in a VE. The AR system enabled subjects to identify potential collisions earlier than their standard view counterparts. Additionally, the impact such a system could have on a tow crew director’s ability to effectively control the towing evolution of an aircraft in an efficient and safe manner was recognized by each subject. The simulated AR system received positive reviews and all participants in the pilot testing felt that exploring a similar AR device for fleet implementation would be worthwhile. After the completion of several minor changes, ATEAR could easily be utilized in an official experiment. Data collected from an official experiment utilizing aircraft maintenance personnel with the requisite skill set would be provide further justification for future development of such an AR system.

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VI. CONCLUSION AND RECOMMENDATIONS

This chapter will briefly summarize the objectives of the research conducted for this thesis and address why we chose to use VR to simulate AR. Additionally, we will briefly revisit current AR initiatives for USN and USMC aircraft maintenance and suggest why a Microsoft HoloLens is not the best AR system for a real-world implementation of the AR system developed in Chapter III.B.2.c. We will also discuss future work that could be conducted in support of the findings from this thesis. A real-world design and implementation of an AR solution that utilizes using modern technology that currently exists within the DoD and commercial sector will be proposed, as well as a possible method of implementing such a device to the fleet.

A. PROJECT OBJECTIVES

The goal of this project was to determine if an AR system could increase situational awareness for tow crew personnel, which in turn, could reduce the likelihood of towing incidents in the future. We opted to use VR to model the towing process, simulate an AR system, and measure human performance for four reasons. First, towing aircraft is inherently a dangerous activity. A mechanical failure from the landing gear or a tow bar breaking during aircraft movement could result in injury to members of the tow crew. Second, towing real aircraft for an experiment has a major impact on manpower in the maintenance department. Doing so would prevent any maintenance from being conducted on the aircraft during that time and would require a full tow crew (six personnel); preventing the maintenance department from accomplishing their daily goals in an already manpower-constrained environment. Third, towing a real aircraft would require an extensive time to reset each scenario for the experiment. Lastly, towing a real aircraft would present a challenging environment to capture objective data due to the time constraints and limited availability of participants.

From a testing standpoint, VR enabled us to measure, subjectively and objectively, the effects of the AR system. We were able to create various towing scenarios that allowed the aircraft to collide with objects like storage containers or other aircraft. We would have never been able to intentionally crash a real aircraft into another aircraft in the real world. essentially replicating an aircraft collision. VR also provided a means of having multiple test subjects conduct multiple towing evolutions for statistical validity. With regard to the design of the AR system, VR allowed us to take a concept, test it, and make changes in a matter of minutes rather than continuing to invest in major iterations of a real-life prototype. Furthermore, VR allowed us to measure each participant's confidence in their ability to foresee a potential aircraft collision.

We chose to build the VE for the VR system around the perspective of the tow crew director because they are ultimately responsible for directing the tow crew and the tow crew's execution of the aircraft tow. Additionally, if an AR system were to be fielded to the fleet operationally, it is unlikely that the USN would invest money in outfitting an entire tow crew with an AR device due to monetary constraints. Due to these reasons, the tow crew director is the best member of the tow crew to outfit with the AR system. Despite there being different forms of VR, the most commonly accepted form of VR is one that utilizes HMDs. We chose to use a HMD as the VR experience method because it provides the most immersion and increased sense of presence to the user. Because of these features, the HMD is more likely encourage tow crew directors to act as they normally would while executing their duties and provide the research team more reliable results from the experiment.

B. FUTURE WORK

1. Official Experiment

Even though the results from our pilot testing showed that an AR system may increase the situational awareness for tow crew directors, an official experiment with the proper personnel would be necessary to further justify the development and implementation of an AR system in the aircraft towing process. Our pilot testing participants were not representative of the personnel who possess the required skill sets to justify the impact the AR system could have on the fleet. Additionally, our analysis consisted of descriptive statistics rather than inferential statistics, which prevented us from formally testing our hypotheses. We would recommend that ATEAR is updated with the changes outlined in Chapter V.B.2 and a formal experiment is conducted using the proper maintenance personnel.

2. Current AR Shortfalls in Naval Aircraft Maintenance

As discussed in Chapter II.E.2.a, the HoloLens is a popular AR HMD used by many manufacturing/repair and maintenance industry. Because it is wireless, relatively light, and a very capable device, it is probably the most popular and actively used AR HMD in industry. Chapter II.F addressed the USN's interest in implementing AR for aircraft maintenance tasks and training via prototype systems such as AR for Maintainers and CARMA. The HoloLens worked well for the use cases demonstrated by the two prototype systems, but it would not be a suitable AR system for operational use by naval aviation maintenance personnel due to its limitations with regard to durability, cranial integration, FOV restrictions, brightness, and power consumption.

a. Durability

Despite having basic impact requirements of ANSI Z87.1, CSA Z94.3 and EN 166, the HoloLens is not durable enough for daily use by young USMC or USN personnel in a maintenance environment (Microsoft, 2019b). The plastic structure of the HoloLens is easy to break and young maintainers are notorious for not taking extra precautions for expensive, fragile equipment and treating it as if it was their own person piece of gear.

b. Cranial Integration

Aircraft maintenance personnel for both the USMC and the USN are required to wear eye, ear, and head protection that is implemented by a device referred to as a cranial (see Figure 54). If the HoloLens was chosen as the AR HMD platform, cranials would need to be redesigned, manufactured, and fielded to the fleet; all of which would cost the USN and USMC a considerable amount of money.

Figure 54. Cranial Example. Source: Clark (n.d.).

c. FOV Restrictions

The outer lens of the HoloLens is a dark tinted color that facilitates the viewing of computer-generated stimuli. The HoloLens only allows 40 percent of ambient light to shine through the main lens (Wagner et al., 2019). Such a lack of transparency is comparable to wearing a pair of sunglasses. Using the HoloLens for aircraft movements during night operations is comparable to towing aircraft with sunglasses on; this poses a significant threat to not only the aircraft but also the tow crew. The lens also covers both eyes of the user, which could have negative implications. In the event the computer-generated stimuli became a distraction or it blocked the view of the aircraft, the tow crew member may lose control of the situation. Ideally, we also want users of the AR HMD to have the ability to use their peripheral vision if they need to. Because of its dark tinted lens that also covers both eyes of the user, the HoloLens does not allow for unimpeded use of one's peripheral vision and is not a suitable platform for use during night operations..

d. Brightness

The HoloLens was not designed to work outdoors. Consequently, the system fails to work seamlessly across a range of brightness levels. The HoloLens makes use of a marker-less registration system, which is made possible by external facing cameras that sense the external environment. However, when an environment is too bright, the cameras are unable accurately view the environment; the same holds true if the environment is too dark (Microsoft, 2019a). Likewise, outdoor lighting is difficult because the brightness levels of light gleaned from the sun can vary over time. To address the brightness issue outdoors, BIM Holoview was able to make the HoloLens much more effective in outdoor environments by mounting a ski goggle lens below the HoloLens lens (Neil, 2018). However, this addition detracts from the already concerning tinted lens discussed above. Because maintainers would use the AR HMD in both day, dusk, and night conditions, the HoloLens is not a suitable AR solution.

e. Power Consumption

Unlike many other AR HMDs, the HoloLens is a fully untethered; meaning there are no cords tying it to a computer or any form of receiver. The HoloLens is powered by a 16,500 mWh battery, which allows the device to be lightweight, but only provides for two to three hours of battery life (Microsoft, 2019b; Rubino, 2016). In many cases depending on the destination or reasoning for towing the aircraft, one towing evolution could take an hour or more. When an aircraft is towed to the wash rack for the aircraft to be washed, the aircraft then needs to be moved to a follow-on location. This process could take an additional hour or more. In the likely event a maintainer accidentally leaves the HoloLens on after the first tow, most likely the battery would be dead; rendering the device useless.

3. Proposed AR Solution

We propose the creation of an AR system that consists of three components: AR display, receiver, and sensor pucks that can be mounted to an aircraft. This proposed system is a minimal, light weight, and purpose-specific system that addresses all of the limitations discussed with the HoloLens above. The AR display would be a single lens mounted to the tow director’s cranial, and the receiver could be designed in such a way that a tow crew director could retain the receiver in their maintenance coveralls. Making the receiver a separate device from the HMD would enable the HMD to be a minimalist, light-weight design. The sensor pucks would be placed in specific locations on the aircraft (see Figure 55 for F/A-18 example). Each sensor would provide position and other sensory data to the AR receiver, which would be processed by the AR system to provide feedback to the user.

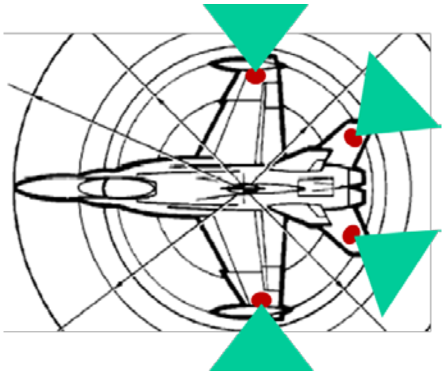

Figure 55. Aircraft Sensor Placement and Sensing Threshold. Adapted from USN (2017).

a. Display Solution

The Office of Naval Research (ONR) Code 34, specializes in sponsoring research efforts aimed at increasing performance of the warfighter. They enhance "warfighter effectiveness and efficiency through bioengineered and biorobotic systems, medical technologies, improved manpower, personnel, training and system design" (Office of Naval Research [ONR], n.d). During a bi-annual program review for the Human Performance, Training, and Education (HPT&E) program review, Michael Strauss presented an update regarding Creative MicroSystems' work on an AR display called the Creative MicroSystems Holographic Imageguide Display (HID) (see Figure 56). Designed for both training and operational use for infantry, artillery, and other ground-specific military applications, the HID is a single eye, indoor and outdoor waveguide AR display. The HID has a natural light throughput efficiency of close to 90 percent, which means only 10 percent of a user's natural view is impaired (Parker et al., 2017). The HID also is capable of showing computer-generated data in full color. The HID could be easily mounted to the top of a tow crew director’s cranial using an interface that allows the device to flip up (when the system is not use) and down (when the system is in use).

Figure 56. Creative MicroSystems Holographic Imageguide Display. Source: Parker et al. (2017).

Similar to the HID from Creative Microsystems, Collins Aerospace also makes a waveguide display called the ERV-30 (see Figure 57). The ERV-30 follows the same concept of the HID and was built for the same use case. Due to their single-eye display, superior performance in both outdoor and indoor environments, full color display, and high natural light throughout efficiency, the HID or the ERV-30 would be great candidates for use in an aircraft towing-specific AR system.

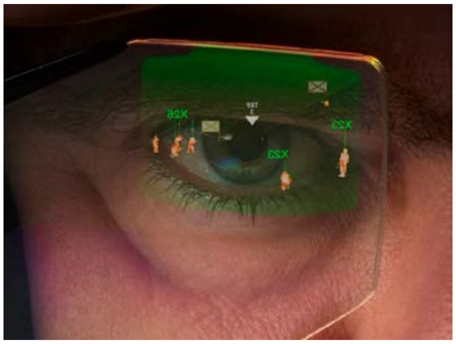

Figure 57. Collins Aerospace Enhanced Reality Vision Systems (ERV-30). Source: Collins Aerospace (n.d.).

b. Networking

The proposed system would be a one way communication device; meaning data would be sent from the sensors mounted on the aircraft to the AR HMD receiver. The data from the sensors would be processed by the AR HMD receiver and presented to the user via the AR display in a manner similar to the AR system tested in ATEAR. At no point in time would the AR HMD or AR receiver push data back to the sensors. Because this system would be utilized for daily operations and also in a deployed setting, emissions control (EMCON) considerations much be taken into account. In light of the USMC' future vision with regard to expeditionary advanced base operations (EABO), the Commandant of the USMC emphasized the importance of signature management and signature reduction for future warfare (United States Marine Corps, 2019).

We foresee three main networking methods the AR system could utilize: WiFi, Bluetooth, and LiFi. Each type of networking platform has its own advantages and disadvantages. However, from an EMCON perspective, WiFi and Bluetooth are the most concerning because they both use radio waves to pass information. Because it utilizes the full spectrum of light (including the frequencies that human eyes cannot detect), LiFi does not utilize any form of radio waves to pass information. Originally introduced by Harald Haas during TEDGlobal in July of 2011, LiFi is a "wireless optical networking technology that uses LEDs for data transmission" (Haas, 2011; LiFi.co, n.d.).

c. Tracking/Registration

For the proposed system, the most plausible tracking system would be one that capitalizes organic tracking from the AR HMD; meaning the AR HMD would need to have at least two (left hand and right hand) external, forward facing cameras that can capture data gleaned from the sensors placed on the aircraft. For the AR system to operate, it would need to know position data for the sensors, the orientation of the sensors, distance data from each sensor to objects close to the aircraft, the position of the AR HMD relative to the sensors mounted on the aircraft, and the orientation of the AR HMD.

(i) Sensor Position Data and Orientation

Presuming that each type of aircraft of the same size (i.e., within 1-2 cm threshold), a standard map could be constructed for each aircraft type. The map would provide known positions and orientation for each sensor to the HMD.

(ii) Sensor Distance from Objects

Similar to a backup sensor on a modern car, each sensor would use light detection and ranging (LiDAR) to measure distances between the sensor and other objects close to the aircraft. Lidar is a method of sensing distances by bouncing light of surfaces (Wasser, n.d.).

(iii) AR HMD Position Data and Orientation

With a standard map for the specific aircraft being used, the AR HMD will have a general idea of where each sensor is located. Using LiFi, each sensor can communicate with the AR receiver. Data passed through the LiFi connection would be the location of the sensor itself (this would facilitate the AR wing tracks used in ATEAR), as well as the distance data captured by each sensor. To keep the amount of data passed to the AR receiver relatively low, sensors could be programmed to flash at a specific frequency for a specific distance.

d. Fleet Implementation

The use of the AR device for towing operations would need to become a requirement to the towing processes outlined in the specific T/M/S IETMs data base and the NAVAIR 17-1-537. Test sets and support equipment (SE) are classified as an aircraft maintenance material readiness list (AMMRL) program asset. Each squadron rates a specific number of particular pieces of equipment. We propose the complete AR system (AR HMD, AR receiver, and sensor pucks) to be stored in a pelican case and classified as an “Aircraft Towing Kit.” The number of towing kits issued to a squadron would be based on the aircraft allowances for those squadrons. For example, an F-35 squadron with 10 aircraft would rate 12 towing kits (one for each aircraft with two spares); squadrons with more aircraft would rate more towing kits.

C. SUMMARY

Despite the cancellation of the official experiment due to the COVID-19 pandemic, the pilot testing results from this project showed promising results. We suggest additional testing to justify the USN’s investment in using AR technologies for aircraft towing. This chapter summarized the testing we conducted and also addressed why a new AR system would need to be constructed for aircraft towing. A general overview of the proposed AR system was discussed, to include how such a system could be implemented in the fleet.

APPENDIX A. TOW CREW DIRECTOR TRAINING SYLLABUS EXAMPLE

⊟AIRCRAFT TOW CREW DIRECTOR TRAINING SYLLABUS AND QUALIFICATION (FA-18 A/B/C/D) (MC)			
⊟ PREREQUISITES		COMPLETE	
⊟ VERIFY Individual holds an active Aircraft Towing Qualification	SUPERVISOR (MC)	COMPLETE	24-May-2015 by SGT [redacted]
⊟ Required Reading		COMPLETE	
⊟ READ NAVAIR-00-80T-96 WP 00300 thru WP 00500	TRAINEE	COMPLETE	18-Jun-2015 by LCPL [redacted]
⊟ READ NAVAIR 17-1-537 WP 00300 thru 00900	TRAINEE	COMPLETE	18-Jun-2015 by LCPL [redacted]
⊟ READ A1 F18AC LMM 000, WP 040 00, 006 00	TRAINEE	COMPLETE	18-Jun-2015 by LCPL [redacted]
⊟ READ A1-F18AC-PCM-000 WP 022 00	TRAINEE	COMPLETE	18-Jun-2015 by LCPL [redacted]
⊟ READ NAVAIR 00-80T-105	TRAINEE	COMPLETE	18-Jun-2015 by LCPL [redacted]
⊟ READ NAVAIR 19-600-175-6-1	TRAINEE	COMPLETE	18-Jun-2015 by LCPL [redacted]
⊟ Briefs		COMPLETE	
⊟ RECEIVE TRAINING ON Maintenance Control Coordination Procedures by maintenance control supervisor	SUPERVISOR (MC)	COMPLETE	24-Jun-2015 by CPL [redacted]
⊟ VERIFY Current Seat Lecture	SUPERVISOR (MC)	COMPLETE	24-Jun-2015 by CPL [redacted]
⊟ RECEIVE TRAINING ON Ordnance/Cartridge Actuated Device (CAD) Safety	QAR W/C 230 (FA-18 A/B/C/D) (MC)	COMPLETE	30-Jun-2015 by SGT [redacted]
⊟ RECEIVE TRAINING ON Quality Assurance Aircraft Movement Safety Requirements by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ On the Job Training		COMPLETE	
⊟ DEMONSTRATE AND DISCUSS Weight limits for aircraft towing by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS Situations that prevent aircraft from being towed by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS Proper tow bar installation by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS Procedures to prepare aircraft for towing by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS Procedures, to include safety precautions, used during aircraft towing by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS Proper hand/arm signals for aircraft towing by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS Procedures for securing aircraft on the flight line by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS Procedures for securing aircraft in the hangar by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS manually folding/spreading wings by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ DEMONSTRATE AND DISCUSS electrically folding/spreading wings by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	14-Jul-2015 by SGT [redacted]
⊟ Practical Application		COMPLETE	
⊟ PERFORM as an aircraft wing walker by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	15-Jul-2015 by SGT [redacted]
⊟ PERFORM as an aircraft tail walker by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	15-Jul-2015 by SGT [redacted]
⊟ PERFORM Preparation of an aircraft for movement in accordance with pre-movement portion of checklist by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	15-Jul-2015 by SGT [redacted]
⊟ PERFORM Properly attachment/removal of tow bar from aircraft by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	15-Jul-2015 by SGT [redacted]
⊟ PERFORM Securing of aircraft on flight line in accordance with the checklist by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	15-Jul-2015 by SGT [redacted]
⊟ PERFORM Securing of aircraft in hangar in accordance with the checklist by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	15-Jul-2015 by SGT [redacted]
⊟ PERFORM Direction of an aircraft movement evolution by a tow director qualified QAR	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	15-Jul-2015 by SGT [redacted]
⊟ Examinations		COMPLETE	
⊟ TEST: ACFT TOW CREW DIRECTOR TRNG (FA-18ABCD-MC)	QUALITY ASSURANCE REPRESENTATIVE (MC)	COMPLETE	100%, Passed on 12-Aug-2015 12-Aug-2015 by SSGT [redacted]

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APPENDIX B. WESS REPORT DATA PULL METHODOLOGY

The Excel file outputted by the WESS for FY2014-FY2019 resulted in thousands of lines in excel; each line representing one mishap that occurred during that year. When searching for specific events, like aircraft collisions during towing evolutions, there is no easy way to find this data. There is no special coding associated with mishaps that delineate towing-related mishaps from maintenance relate mishaps. The only viable method of searching for the desired data in this case was to utilize the "CTRL + F" function native to excel and search for key words in the mishap narrative columns. A search was conducted to find all incidents that contained the terms "tow," "tow tractor," and "move." The goal of this data pull was to find incidents that occurred specifically from towing aircraft into other aircraft. After this search, the document was able to be reduced to 162 mishaps. After examining the narratives from the data set at this point, it became obvious that some of the mishaps were not a result from towing at all. Some incidents were maintenance related from other maintenance actions like a main landing gear door breaking during a jack and cycle and a propeller collision during a pilot taxiing the aircraft near a hangar. After manually reading the brief narratives associated with each mishap, the list was narrowed down to 155 total.

At this point, the data set of 155 included only towing related incidents from FY2014-FY2019. Many incidents in this data set included those where an issue occurred during towing the aircraft that had nothing to do with a collision between the aircraft and another object on the flight line. The majority of the data spoke to tow bars breaking during the towing evolution, the tow tractor driver hitting an object with the tow tractor, or some other issue with the aircraft during the towing process. The data was further parsed down using a word search for "collide," "collision," "into," and "hit." The resulting data set yielded a total of 59 towing-related incidents, from FY2014-FY2019, due to accidentally towing an aircraft into another object. The term towing-related incidents is utilized because this figure includes HAZREPs, which are not formally classified as a mishap. It is important to note that while this project focuses the towing process of an F/A-18, this data set includes all types of aircraft within the USN.

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APPENDIX C. DATA ANALYSIS PYTHON CODE

```
import csv
import glob
import errno
import statistics
import math
path = 'C:/Users/colto/OneDrive - Naval Postgraduate School/Thesis
Resources/Thesis/Thesis/Analysis/ATEARpilotTesting\ATEARReadOuts/pilot7/*.csv'
files = glob.glob(path)
##used for calculating distance
recentSpeed = 0.00
triggerTimeforSpeed = 0.00
collisionTimeforSpeed = 0.00

for name in files:
 try:
 #reads each file
 with open(name, newline='') as f:
 f_reader = csv.reader(f, delimiter=',')

 #Verifies we read each entry
 count = 0
 totalLine = ''
 speedControl = False
 recordSpeed = False
 speedArray = []
 reactionTime = 0.00
 objectCollided = False
 tractorStopped = False

 for line in f_reader:

 try:
 #each 'line' represents column #
 simTime = line[0]
 task = line[1]
 speed = line[2]

 #print StopTowTractor
 if task == ('Stop Tractor Triggered'):
 print(task + ',' + simTime)
 tractorStopped = True
 if speedControl == True:
 print('Mean is,', statistics.mean(speedArray))
 print('Stdev is,', statistics.stdev(speedArray))
 print('Most recent speed is,',
                                  speedArray[len(speedArray)-1])

 recordSpeed = False
 triggerTimeforSpeed = float(simTime)
 recentSpeed = float(speedArray[len(speedArray)-1])
 speedArray = []
```

```
#print FinishScenario
if task == ('Finish Scenario Triggered'):
if len(speedArray) > 0:
if speedControl == True:
print('Mean is,', statistics.mean(speedArray))
print('Stdev is,', statistics.stdev(speedArray))
print('Most recent speed is,',
                                  speedArray[len(speedArray)-1])
             recordSpeed = False

if recordSpeed == True :
if speed != '' :
if task == 'Tractor Speed':
speedArray.append(float(speed))
#print QuestionResponse
if task == ('Question A'):
print(task + ',' + speed)
if task == ('Question B'):
print(task + ',' + speed)
#print subjectID
if task == ('Subject ID'):
print(task +','+ speed)
#print AR status
if task == ('Is AR On'):
print(task + ',' + speed)
#print Speed Control
if task == ('Can Control Tractor Speed'):
print(task + ',' + speed)
if speed == 'Yes':
speedControl = True
#print EnvironmentType
if task == ('Running Scenario'):
print(speed)
#print StartScenario
if task == ('Start Scenario Triggered'):
#print(task + ',' + simTime)
recordSpeed = True

#print ObjectCollisionTrigger
if task == ('Object Collision Triggered'):
#print(task + ',' + simTime)
objectCollided = True
collisionTimeforSpeed = float(simTime)

                    print('Distance is,' , (collisionTimeforSpeed –
                           triggerTimeforSpeed) * recentSpeed)
collisionTimeforSpeed = 0.00
triggerTimeforSpeed = 0.00
recentSpeed = 0.00
if objectCollided == tractorStopped:
print('Collison Prediction' + ',' + 'Correct')
objectCollided = False
tractorStopped = False
if objectCollided != tractorStopped:
print('Collison Prediction' + ',' + 'Incorrect')
objectCollided = False
tractorStopped = False
```

```
except:
break
except IOError as exc:
if exc.errno != errno.EISDIR:raise
```

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APPENDIX D. DATA ANALYSIS CODE OUTPUT

```
Subject ID,pilot3
Is AR On,Yes
Can Control Tractor Speed,No
Environment 1 - Miss
Question B,10
Environment 2 - Hit
Distance is, 0.0
Collison Prediction,Incorrect
Question B,8.495583
Environment 3 - Caution
Question B,10
Environment 4 - Danger
Question B,10
Scenario 4 - Return to Hangar
Question B,6.494386
Subject ID,pilot3
Is AR On,Yes
Can Control Tractor Speed,Yes
Environment 1 - Danger
Mean is, 1.6880823323232323
Stdev is, 0.4953860572290325
Most recent speed is, 2.006281
Question B,10
Environment 2 - Miss
Mean is, 1.7202238420212765
Stdev is, 0.4770769538637313
Most recent speed is, 1.998462
Question B,10
Environment 3 - Danger
Mean is, 1.668345347368421
Stdev is, 0.5014945866920686
Most recent speed is, 1.998957
Question B,10
Environment 4 - Caution
Mean is, 1.711121535501355
Stdev is, 0.48426365872627497
Most recent speed is, 2.006404
Question B,10
Scenario 4 - Return to Hangar
Distance is, 0.0
Collison Prediction,Incorrect
Mean is, 1.7023815471153847
```

(continues until all scenarios are processed)

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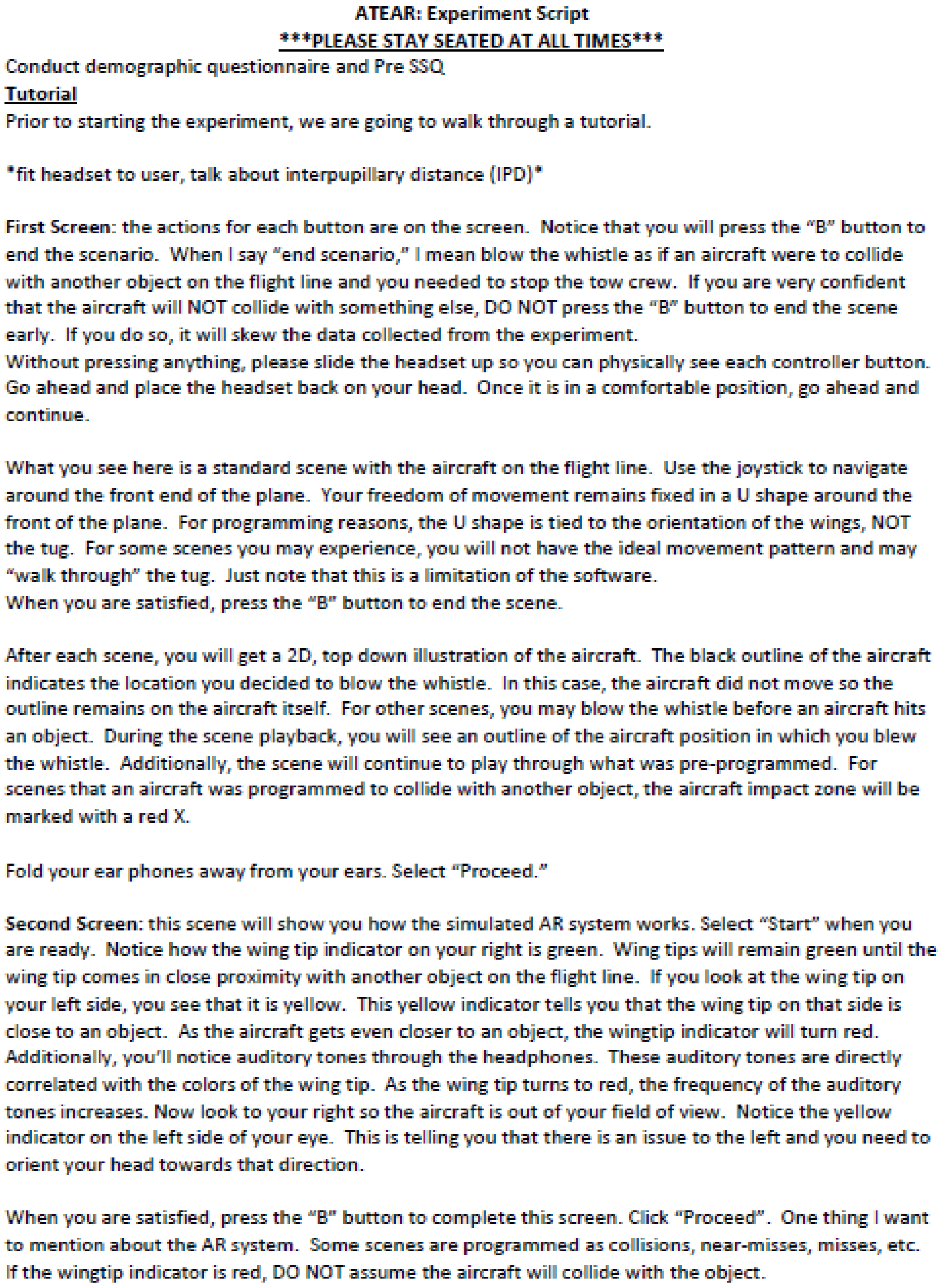
APPENDIX E. PILOT TESTING EXPERIMENT SCRIPT



ATEAR: Experiment Script

*****PLEASE STAY SEATED AT ALL TIMES*****

Conduct demographic questionnaire and Pre SSQ

Tutorial

Prior to starting the experiment, we are going to walk through a tutorial.

fit headset to user, talk about interpupillary distance (IPD)

First Screen: the actions for each button are on the screen. Notice that you will press the "B" button to end the scenario. When I say "end scenario," I mean blow the whistle as if an aircraft were to collide with another object on the flight line and you needed to stop the tow crew. If you are very confident that the aircraft will NOT collide with something else, DO NOT press the "B" button to end the scene early. If you do so, it will skew the data collected from the experiment.

Without pressing anything, please slide the headset up so you can physically see each controller button. Go ahead and place the headset back on your head. Once it is in a comfortable position, go ahead and continue.

What you see here is a standard scene with the aircraft on the flight line. Use the joystick to navigate around the front end of the plane. Your freedom of movement remains fixed in a U shape around the front of the plane. For programming reasons, the U shape is tied to the orientation of the wings, NOT the tug. For some scenes you may experience, you will not have the ideal movement pattern and may "walk through" the tug. Just note that this is a limitation of the software.

When you are satisfied, press the "B" button to end the scene.

After each scene, you will get a 2D, top down illustration of the aircraft. The black outline of the aircraft indicates the location you decided to blow the whistle. In this case, the aircraft did not move so the outline remains on the aircraft itself. For other scenes, you may blow the whistle before an aircraft hits an object. During the scene playback, you will see an outline of the aircraft position in which you blew the whistle. Additionally, the scene will continue to play through what was pre-programmed. For scenes that an aircraft was programmed to collide with another object, the aircraft impact zone will be marked with a red X.

Fold your ear phones away from your ears. Select "Proceed."

Second Screen: this scene will show you how the simulated AR system works. Select "Start" when you are ready. Notice how the wing tip indicator on your right is green. Wing tips will remain green until the wing tip comes in close proximity with another object on the flight line. If you look at the wing tip on your left side, you see that it is yellow. This yellow indicator tells you that the wing tip on that side is close to an object. As the aircraft gets even closer to an object, the wingtip indicator will turn red. Additionally, you'll notice auditory tones through the headphones. These auditory tones are directly correlated with the colors of the wing tip. As the wing tip turns to red, the frequency of the auditory tones increases. Now look to your right so the aircraft is out of your field of view. Notice the yellow indicator on the left side of your eye. This is telling you that there is an issue to the left and you need to orient your head towards that direction.

When you are satisfied, press the "B" button to complete this screen. Click "Proceed". One thing I want to mention about the AR system. Some scenes are programmed as collisions, near-misses, misses, etc. If the wingtip indicator is red, DO NOT assume the aircraft will collide with the object.

Third Screen: for some scenes, you will have the ability to control the speed of the tow tractor. We intend to utilize this data to see the level of confidence you have in your ability to foresee an aircraft collision. When ready, click start.

Pull and release the trigger. You'll notice your speed increases and decreases accordingly.

When you're finished, press the "B" button to end the scene.

Go ahead and select "Proceed." The tutorial is now complete.

Experiment

For the first 5 scenarios, you will not be able to control aircraft speed. For the last 5, you will be able to control aircraft movement speed. At the end of each scene, you will be asked to enter your confidence in your ability to identify a potential collision. Pay attention to the wording of each question because they do vary slightly. To enter your answer for each question, simply slide the selection bar to your desired location and select "Proceed."

Do you have any questions? *If no, begin the experiment*

Your Subject ID indicates which set of scenarios you will do first.

	Odd Subject ID	Even Subject ID
Set 1	AR	Standard View
Set 2	AR w/ Speed	Standard View w/ Speed
Set 3	Standard View	AR
Set 4	Standard View w/ Speed	AR w/ Speed

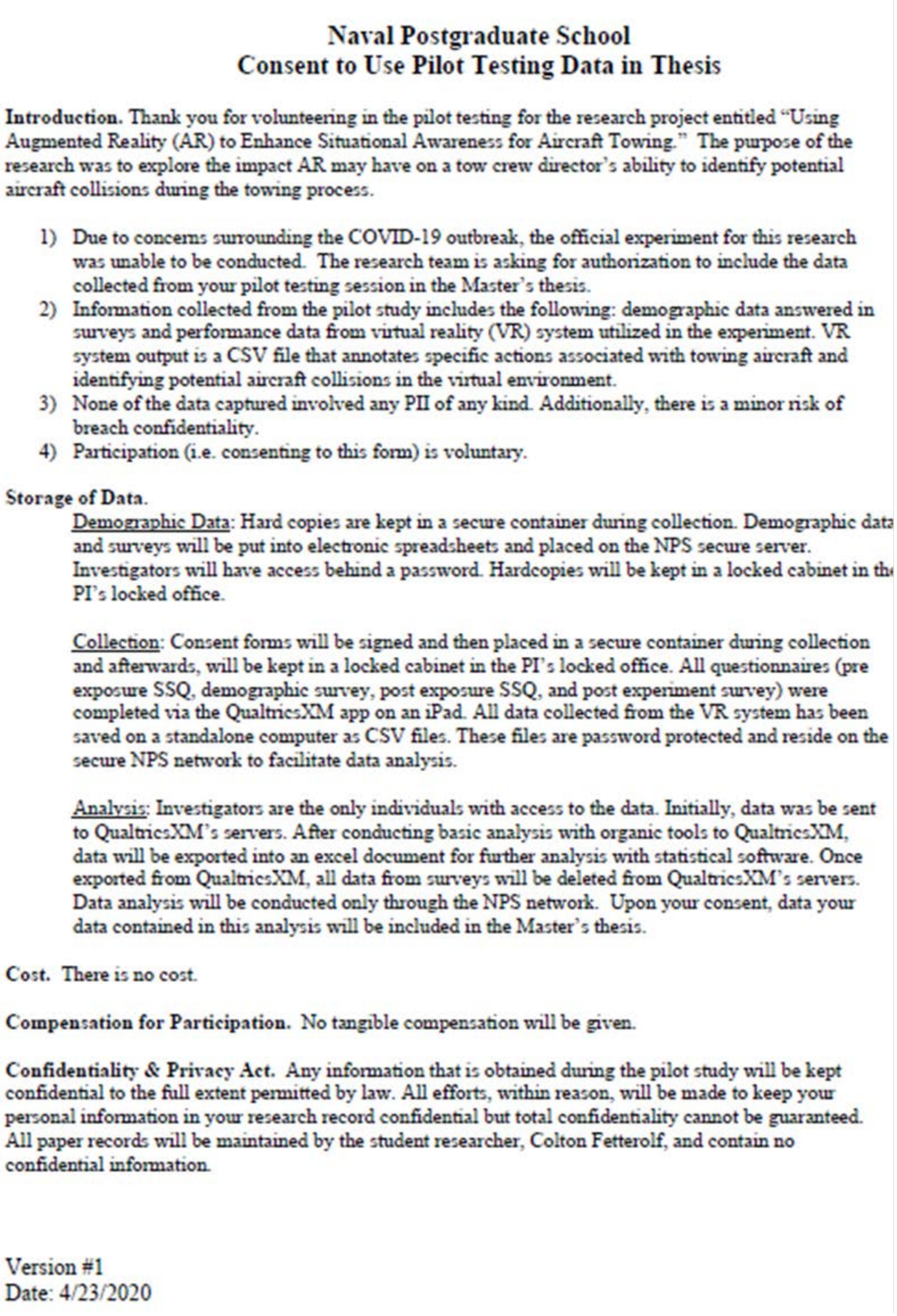
After First Session is Completed:

- Contrast sensitivity test
- Cognitive processing speed test
    - There are tutorials in the test. No rush.

Conduct opposite sets

Conduct post survey and Post SSQ

APPENDIX F. ATEAR PILOT TESTING CONSENT FORM



Naval Postgraduate School
Consent to Use Pilot Testing Data in Thesis

Introduction. Thank you for volunteering in the pilot testing for the research project entitled "Using Augmented Reality (AR) to Enhance Situational Awareness for Aircraft Towing." The purpose of the research was to explore the impact AR may have on a tow crew director's ability to identify potential aircraft collisions during the towing process.

1) Due to concerns surrounding the COVID-19 outbreak, the official experiment for this research was unable to be conducted. The research team is asking for authorization to include the data collected from your pilot testing session in the Master's thesis.
2) Information collected from the pilot study includes the following: demographic data answered in surveys and performance data from virtual reality (VR) system utilized in the experiment. VR system output is a CSV file that annotates specific actions associated with towing aircraft and identifying potential aircraft collisions in the virtual environment.
3) None of the data captured involved any PII of any kind. Additionally, there is a minor risk of breach confidentiality.
4) Participation (i.e. consenting to this form) is voluntary.

Storage of Data.

<u>Demographic Data</u>: Hard copies are kept in a secure container during collection. Demographic dat and surveys will be put into electronic spreadsheets and placed on the NPS secure server. Investigators will have access behind a password. Hardcopies will be kept in a locked cabinet in th PI's locked office.

<u>Collection</u>: Consent forms will be signed and then placed in a secure container during collection and afterwards, will be kept in a locked cabinet in the PI's locked office. All questionnaires (pre exposure SSQ, demographic survey, post exposure SSQ, and post experiment survey) were completed via the QualtricsXM app on an iPad. All data collected from the VR system has been saved on a standalone computer as CSV files. These files are password protected and reside on the secure NPS network to facilitate data analysis.

<u>Analysis</u>: Investigators are the only individuals with access to the data. Initially, data was be sent to QualtricsXM's servers. After conducting basic analysis with organic tools to QualtricsXM, data will be exported into an excel document for further analysis with statistical software. Once exported from QualtricsXM, all data from surveys will be deleted from QualtricsXM's servers. Data analysis will be conducted only through the NPS network. Upon your consent, data your data contained in this analysis will be included in the Master's thesis.

Cost. There is no cost.

Compensation for Participation. No tangible compensation will be given.

Confidentiality & Privacy Act. Any information that is obtained during the pilot study will be kept confidential to the full extent permitted by law. All efforts, within reason, will be made to keep your personal information in your research record confidential but total confidentiality cannot be guaranteed. All paper records will be maintained by the student researcher, Colton Fetterolf, and contain no confidential information.

Version #1
Date: 4/23/2020

Points of Contact. If you have any questions or comments about the research, or you experience an injury or have questions about any discomforts that you experience while taking part in this study please contact the Principal Investigator, Dr. Quinn Kennedy, (831) 656-2618, mqkenned@nps.edu. Questions about your rights as a research subject or any other concerns may be addressed to the Navy Postgraduate School IRB Chair, Dr. Larry Shattuck, 831-656-2473, lgshattu@nps.edu.

Statement of Consent. I have read the information provided above. I have been given the opportunity to ask questions and all the questions have been answered to my satisfaction. I have been provided a copy of this form for my records and I agree to participate in this study. I understand that by agreeing to participate in this research and signing this form, I do not waive any of my legal rights.

☐ I consent to the release of my pilot testing data for analysis in the Master's thesis associated with this research.

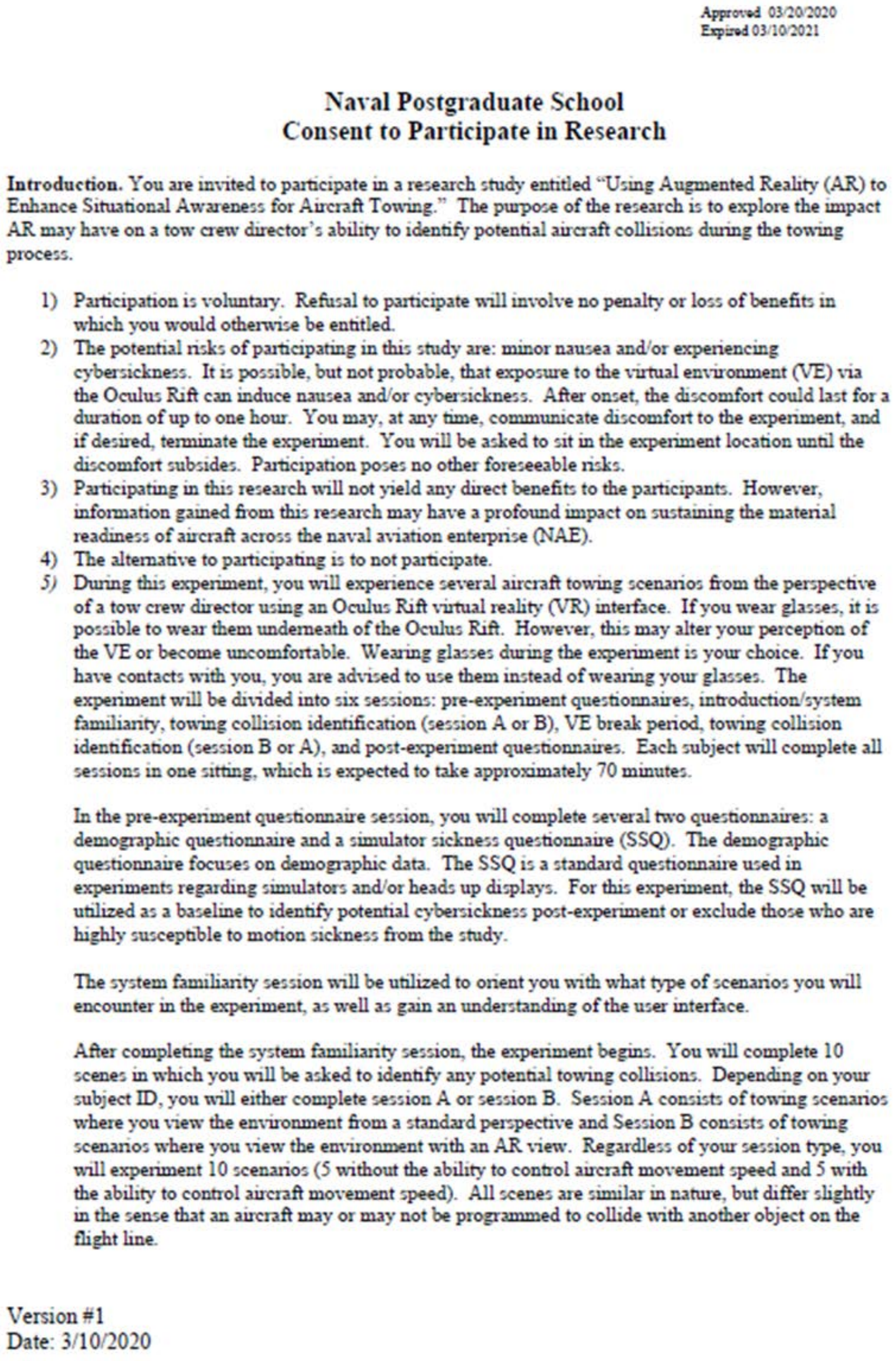
☐ I do not consent to the release of my pilot testing data for analysis in the Master's thesis associated with this research.

Signature of Participant

Date

Version #1
Date: 4/23/2020

APPENDIX G. ATEAR EXPERIMENT CONSENT FORM



Approved 03/20/2020
Expired 03/10/2021

Naval Postgraduate School
Consent to Participate in Research

Introduction. You are invited to participate in a research study entitled "Using Augmented Reality (AR) to Enhance Situational Awareness for Aircraft Towing." The purpose of the research is to explore the impact AR may have on a tow crew director's ability to identify potential aircraft collisions during the towing process.

1) Participation is voluntary. Refusal to participate will involve no penalty or loss of benefits in which you would otherwise be entitled.
2) The potential risks of participating in this study are: minor nausea and/or experiencing cybersickness. It is possible, but not probable, that exposure to the virtual environment (VE) via the Oculus Rift can induce nausea and/or cybersickness. After onset, the discomfort could last for a duration of up to one hour. You may, at any time, communicate discomfort to the experiment, and if desired, terminate the experiment. You will be asked to sit in the experiment location until the discomfort subsides. Participation poses no other foreseeable risks.
3) Participating in this research will not yield any direct benefits to the participants. However, information gained from this research may have a profound impact on sustaining the material readiness of aircraft across the naval aviation enterprise (NAE).
4) The alternative to participating is to not participate.
5) During this experiment, you will experience several aircraft towing scenarios from the perspective of a tow crew director using an Oculus Rift virtual reality (VR) interface. If you wear glasses, it is possible to wear them underneath of the Oculus Rift. However, this may alter your perception of the VE or become uncomfortable. Wearing glasses during the experiment is your choice. If you have contacts with you, you are advised to use them instead of wearing your glasses. The experiment will be divided into six sessions: pre-experiment questionnaires, introduction/system familiarity, towing collision identification (session A or B), VE break period, towing collision identification (session B or A), and post-experiment questionnaires. Each subject will complete all sessions in one sitting, which is expected to take approximately 70 minutes.

   In the pre-experiment questionnaire session, you will complete several two questionnaires: a demographic questionnaire and a simulator sickness questionnaire (SSQ). The demographic questionnaire focuses on demographic data. The SSQ is a standard questionnaire used in experiments regarding simulators and/or heads up displays. For this experiment, the SSQ will be utilized as a baseline to identify potential cybersickness post-experiment or exclude those who are highly susceptible to motion sickness from the study.

   The system familiarity session will be utilized to orient you with what type of scenarios you will encounter in the experiment, as well as gain an understanding of the user interface.

   After completing the system familiarity session, the experiment begins. You will complete 10 scenes in which you will be asked to identify any potential towing collisions. Depending on your subject ID, you will either complete session A or session B. Session A consists of towing scenarios where you view the environment from a standard perspective and Session B consists of towing scenarios where you view the environment with an AR view. Regardless of your session type, you will experiment 10 scenarios (5 without the ability to control aircraft movement speed and 5 with the ability to control aircraft movement speed). All scenes are similar in nature, but differ slightly in the sense that an aircraft may or may not be programmed to collide with another object on the flight line.

Version #1
Date: 3/10/2020

After your first VR session, you will conduct a VE break period. During this time, you will take off the VR system and execute two tasks. First, you will complete a contrast sensitivity test, which is similar to the eye chart you complete during your regular eye exam. Second, you will conduct a cognitive processing speed test using an android tablet. The purpose of both tasks is to provide insight to the researchers on factors that could affect a person's ability to identify towing collisions.

Following the VE break period, you will conduct the opposite session type from your first VR session. If you complete Session A first, you will now complete Session B. This VR session consists of the same number of scenarios and will take approximately the same amount of time to complete.

After completing your second VR session, you will conduct the post-experiment questionnaire session. In this session, you will complete a post-experiment SSQ which will be utilized to identify cybersickness after exposure to the VE. Additionally, you will answer questions regarding your perceived performance in the experiment, potential utilization of AR technology during towing evolutions, and overall usability of the system.

We expect between 15 and 40 participants. The procedures for the experiment are completely new, designed specifically for this research, and will serve no purpose other than research. You will not be recorded from an audio or video perspective. However, your results will be recorded by the system and placed in an excel file for analysis by the research team. No confidential information will be retained by any member of the research team.

The experiment will take place in a Navy or Marine Corps, F/A-18 squadron's ready room with no interruptions. This area is generally located near the administrative section of the squadron hangar, is indoors, and considered a comfortable, relatively quiet environment. In the event you exert symptoms of severe sickness related to the VR system, your chain of command will be notified, as well as medical personnel.

Cost. There is no cost to participate in this research study.

Compensation for Participation. No tangible compensation will be given.

Confidentiality & Privacy Act. Any information that is obtained during this study will be kept confidential to the full extent permitted by law. All efforts, within reason, will be made to keep your personal information in your research record confidential but total confidentiality cannot be guaranteed. All paper records will be maintained by the student researcher, Colton Fetterolf, and will contain no confidential information.

Points of Contact. If you have any questions or comments about the research, or you experience an injury or have questions about any discomforts that you experience while taking part in this study please contact the Principal Investigator, Dr. Quinn Kennedy, (831) 656-2618, mqkenned@nps.edu. Questions about your rights as a research subject or any other concerns may be addressed to the Navy Postgraduate School IRB Chair, Dr. Larry Shattuck, 831-656-2473, lgshattu@nps.edu.

Statement of Consent. I have read the information provided above. I have been given the opportunity to ask questions and all the questions have been answered to my satisfaction. I have been provided a copy of this form for my records and I agree to participate in this study. I understand that by agreeing to participate in this research and signing this form, I do not waive any of my legal rights.

Approved 03/20/2020
Expired 03/10/2021

☐ I consent to participate in the research study.

☐ I do not consent to participate in the research study.

Signature of Participant Date

Version #1
Date: 3/10/2020

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APPENDIX H. ATEAR DEMOGRAPHIC SURVEY

Start of Block: Default Question Block

Q1 Please enter your subject ID (ex. 3):

____

Q2 Please enter today's date (ex. 2/5/2020):

____

Q3 Please enter your age (ex. 25):

____

Q4 Select your gender:

○ Male (1)

○ Female (2)

Q5 What is your preferred writing hand?

○ Left (1)

○ Right (2)

○ Ambidextrous (3)

Q6 Do you wear corrective lenses for your eyes?

○ Yes (1)

○ No (2)

Display This Question:

If Do you wear corrective lenses for your eyes? = Yes

Q7 What is your uncorrected vision (ex. 20/400)? If you do not know your uncorrected vision, please type 0000 in the box below.

____

Display This Question:

If Do you wear corrective lenses for your eyes? = Yes

Q8 Will you be wearing glasses or contacts for this experiment?

○ Yes (1)

○ No (2)

Q11 Please select your branch of military service:

○ USMC (1)

○ USN (2)

Q25 Please enter your current squadron (ex. VMFA-323 or VFA-122):

____

Q9 How many years have you served in the military (ex. 2.5)?

____

Display This Question:

If Please select your branch of military service: = USMC

Q10 Please select your rank:

▼ Pvt (1) ... MGySgt (9)

Display This Question:

If Please select your branch of military service: = USN

Q12 Please select your rank:

▼ SR (1) ... MCPO (9)

Q13 Please enter your MOS (USMC) or NEC (USN):

____

Q14 How many total years have you served at the organizational/squadron level?

- ○ Less than 1 (8)
- ○ 1-2 (1)
- ○ 3-4 (2)
- ○ 5-6 (3)
- ○ 7-8 (4)
- ○ 9-10 (5)
- ○ 11+ (7)

Q15 Is your tow crew director qualification currently active?

- ○ Yes (1)
- ○ No (2)

Q17 How many total years have you been tow crew director qualified?

- ○ Less than 1 (7)
- ○ 1-2 (1)
- ○ 3-4 (2)
- ○ 5-6 (3)
- ○ 7-8 (4)
- ○ 9-10 (5)
- ○ 11+ (6)

Q18 Have you ever directly witnessed a towing mishap with an F/A-18?

○ Yes (1)

○ No (2)

Display This Question:

If Have you ever directly witnessed a towing mishap with an F/A-18? = Yes

Q19 Were you a member of the tow crew during the mishap?

○ Yes (1)

○ No (2)

Display This Question:

If Were you a member of the tow crew during the mishap? = Yes

Q20 Were you serving as the tow crew director during the mishap?

○ Yes (1)

○ No (2)

Q21 Have you ever utilized virtual reality (VR) displays?

○ Yes (1)

○ No (2)

Q23 How many hours a week do you play desktop computer games?

○ 0 (7)

○ 1-2 (1)

○ 3-4 (2)

○ 5-6 (3)

○ 7-8 (4)

○ 9-10 (5)

○ 11+ (6)

Q24 Are you susceptible to motion sickness?

○ Yes (1)

○ Maybe (2)

○ No (3)

End of Block: Default Question Block

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APPENDIX I. ATEAR SSQ

Start of Block: Default Question Block

Q23 Please enter your subject ID (ex. 3):

____

Q24 Please enter today's date (ex. 2/5/2020):

____

Q1 For the following questions, please select the degree to which each symptom is affecting you right now.

Q2 General Discomfort

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q3 Fatigue

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q4 Headache

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q5 Eye Strain

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q6 Difficulty Focusing

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q7 Salivation Increasing

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q8 Sweating

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q9 Nausea

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q10 Difficulty Concentrating

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q11 Fullness of Head (your head feels heavy)

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q12 Blurred Vision

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q14 Dizziness With Eyes Open

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q13 Dizziness With Eyes Closed

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q15 Vertigo (loss of orientation with respect to vertical upright)

○ None (1)

○ Slight (2)

○ Moderate (3)

○ Severe (4)

Q16 Stomach Awareness (upset stomach, just short of nausea)

- ○ None (1)
- ○ Slight (2)
- ○ Moderate (3)
- ○ Severe (4)

Q17 Burping

- ○ None (1)
- ○ Slight (2)
- ○ Moderate (3)
- ○ Severe (4)

End of Block: Default Question Block

*same for both pre and post-experiment

APPENDIX J. ATEAR POST-EXPERIMENT SURVEY

Start of Block: Default Question Block

Q1 Please enter your subject ID (ex. 3):

____

Q2 Please enter today's date (ex. 2/5/2020):

____

Q3 Could you see the towing scenarios clearly in the Oculus Rift?

○ Yes (1)

○ No (2)

Display This Question:

If Could you see the towing scenarios clearly in the Oculus Rift? = No

Q4 Were you wearing corrective lenses?

○ Yes (1)

○ No (2)

Display This Question:

If Were you wearing corrective lenses? = Yes

Q5 Were you wearing glasses?

○ Yes (1)

○ No (2)

Display This Question:

If Were you wearing glasses? = No

Q6 Were you wearing contact lenses?

○ Yes (1)

○ No (2)

Display This Question:

If Could you see the towing scenarios clearly in the Oculus Rift? = No

Q7 Why do you feel that you could not see the towing scenarios clearly?

____

____

____

____

____

Q8 Did the towing scenes accurately represent towing an F/A-18? (We understand the entire process is not captured. Replicating the entire tow process is out of the scope of this project):

○ Yes (1)

○ No (2)

Q9 Did you have enough time to gain an understanding of your situation and identify potential collision areas for aircraft in each scene?

○ Yes (1)

○ No (2)

Display This Question:

If Did you have enough time to gain an understanding of your situation and identify potential collis... = No

Q10 Which scene(s) did you feel like you did not have enough time allotted to make a decision (select all that apply)?

☐ Outdoor towing around storage containers (1)

☐ Outdoor towing around aircraft (2)

☐ Indoor towing inside the hangar (3)

Q11 On a scale of 1 to 10 (10 being the most difficult), rate the difficulty of utilizing the AR system:

	0 10
Slide the marker: ()	

Q12 What impact did the AR display have on your ability to understand the location of the aircraft in reference to other items (i.e., aircraft, boxes, support equipment) on the flight line?

○ Helped Understanding (1)

○ No Effect (2)

○ Reduced Understanding (3)

Q14 On a scale of 1 to 10 (10 being the most confident), rate your confidence in towing with the AR system?

	0 10
Slide the marker: ()	

Q13 If a similar AR system was fielded to the fleet and utilized for the towing aircraft, do you think the number of towing-related incidents would decrease?

○ Yes (1)

○ No (2)

Q15 Do you think a similar AR system should be incorporated into the towing process across the fleet?

○ Yes (1)

○ No (2)

Display This Question:

If Do you think a similar AR system should be incorporated into the towing process across the fleet? = Yes

Q16 Why do you think a similar AR system should be incorporated into the towing process?

____

____

____

____

____

Display This Question:

If Do you think a similar AR system should be incorporated into the towing process across the fleet? = No

Q17 Why do you think a similar AR system should NOT be incorporated into the towing process?

____

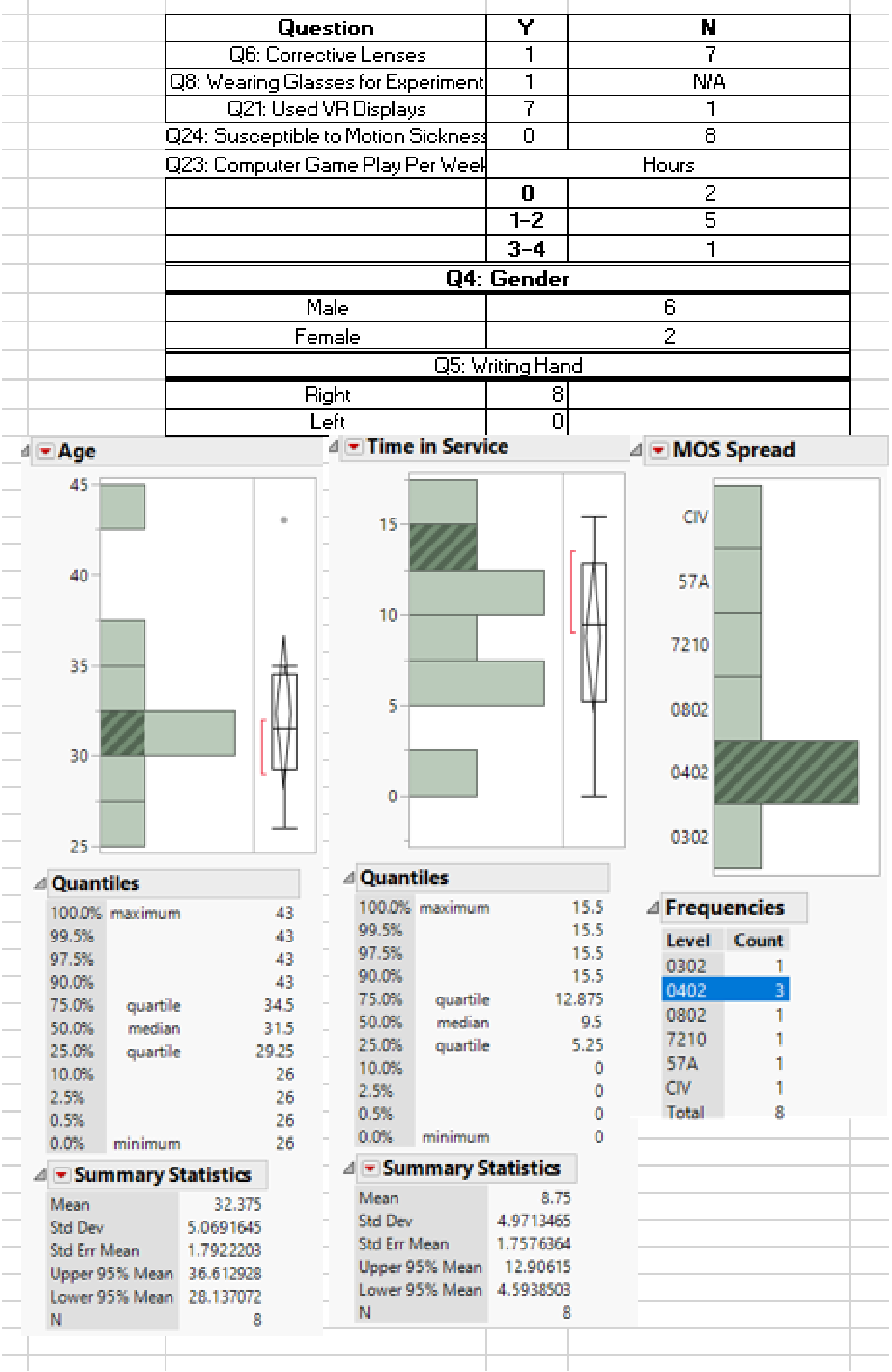
____

____

____

____

APPENDIX K. DEMOGRAPHIC SURVEY RESULTS



Question	Y	N
Q6: Corrective Lenses	1	7
Q8: Wearing Glasses for Experiment	1	N/A
Q21: Used VR Displays	7	1
Q24: Susceptible to Motion Sickness	0	8
Q23: Computer Game Play Per Week	Hours	
	0	2
	1-2	5
	3-4	1

Q4: Gender	
Male	6
Female	2

Q5: Writing Hand	
Right	8
Left	0

Age

Quantiles

100.0%	maximum	43
99.5%		43
97.5%		43
90.0%		43
75.0%	quartile	34.5
50.0%	median	31.5
25.0%	quartile	29.25
10.0%		26
2.5%		26
0.5%		26
0.0%	minimum	26

Summary Statistics

Mean	32.375
Std Dev	5.0691645
Std Err Mean	1.7922203
Upper 95% Mean	36.612928
Lower 95% Mean	28.137072
N	8

Time in Service

Quantiles

100.0%	maximum	15.5
99.5%		15.5
97.5%		15.5
90.0%		15.5
75.0%	quartile	12.875
50.0%	median	9.5
25.0%	quartile	5.25
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

Mean	8.75
Std Dev	4.9713465
Std Err Mean	1.7576364
Upper 95% Mean	12.90615
Lower 95% Mean	4.5938503
N	8

MOS Spread

Frequencies

Level	Count
0302	1
0402	3
0802	1
7210	1
57A	1
CIV	1
Total	8

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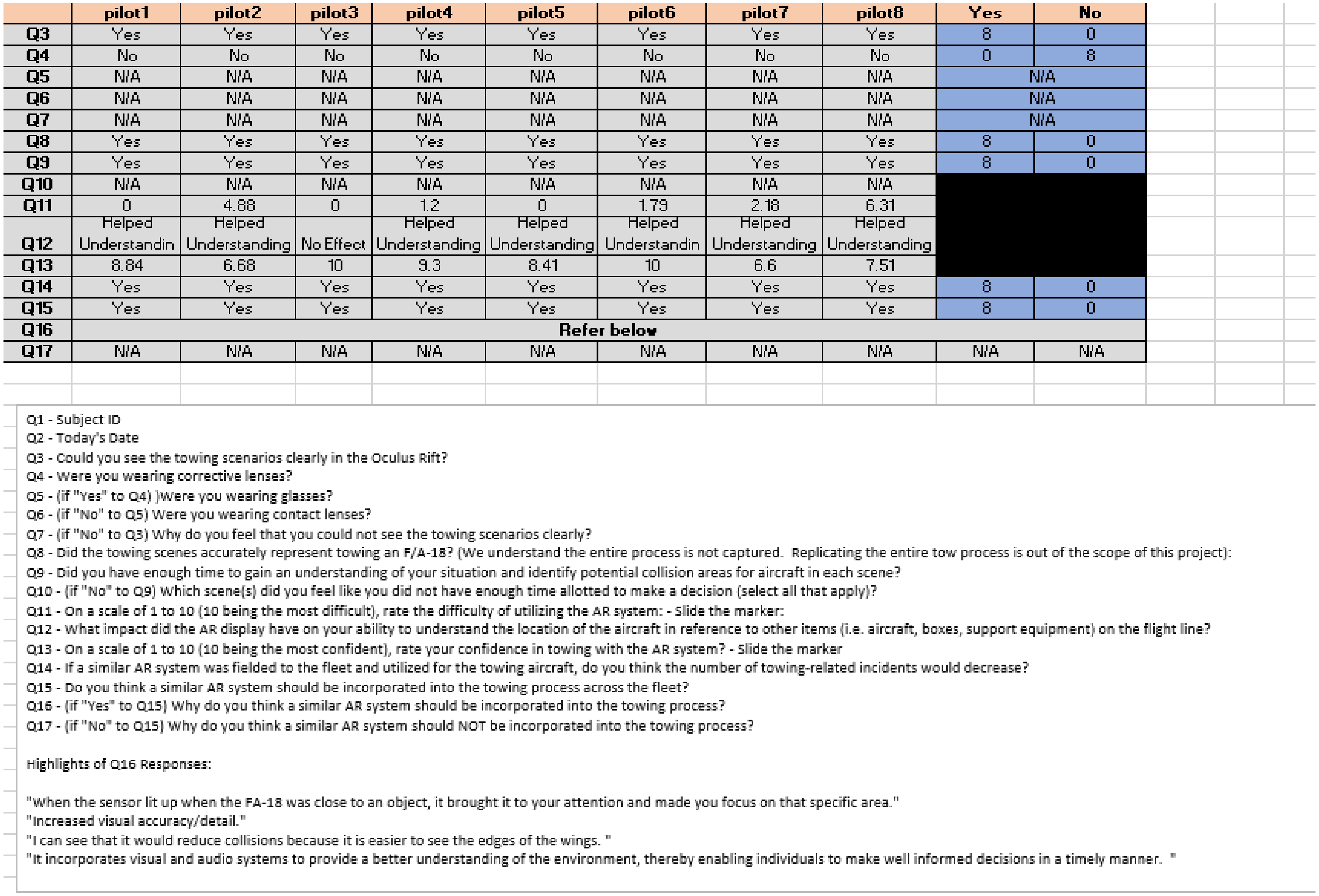
APPENDIX L. POST-EXPERIMENT SURVEY DATA

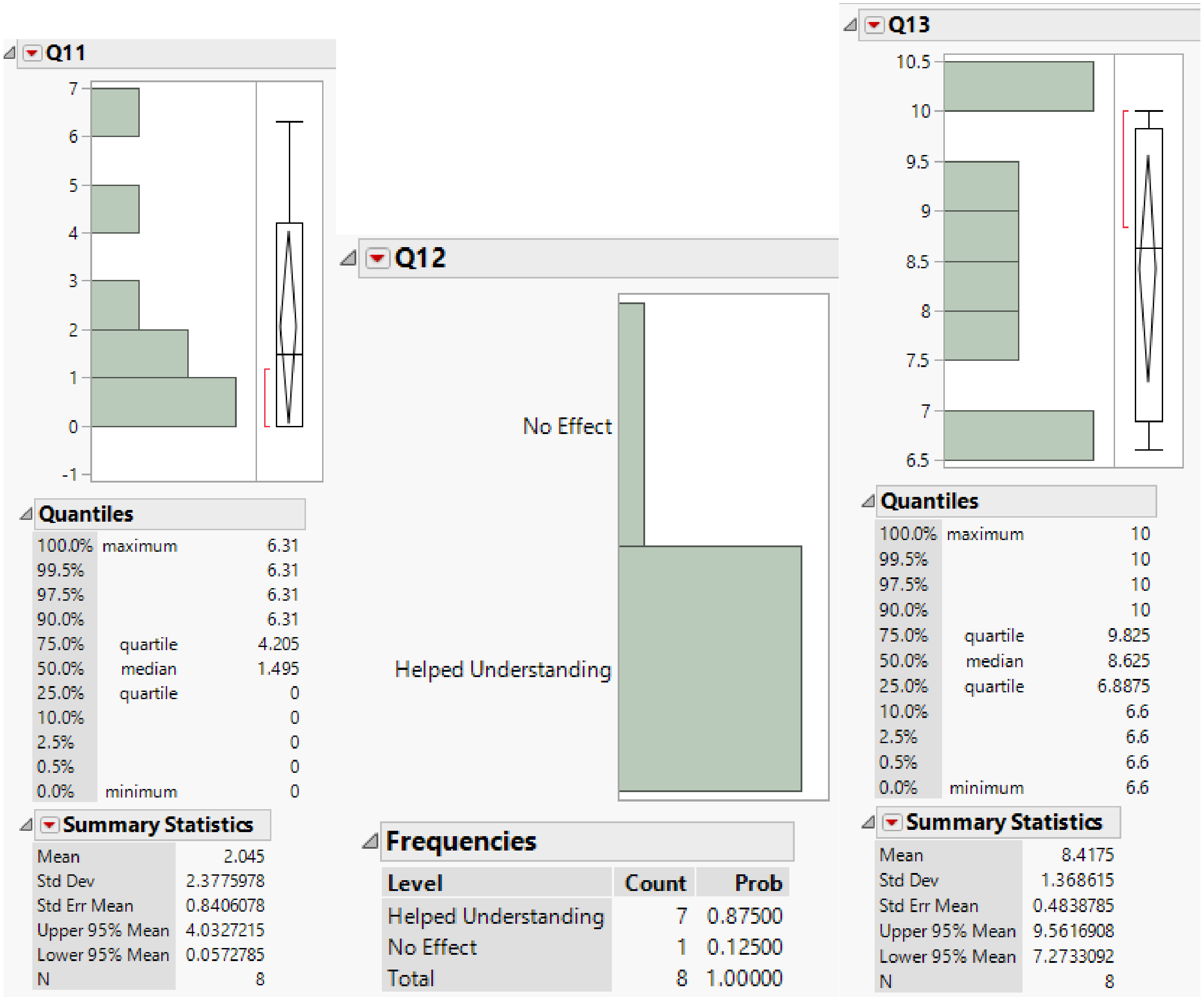


	pilot1	pilot2	pilot3	pilot4	pilot5	pilot6	pilot7	pilot8	Yes	No
Q3	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8	0
Q4	No	No	No	No	No	No	No	No	0	8
Q5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Q6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Q7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Q8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8	0
Q9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8	0
Q10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		
Q11	0	4.88	0	1.2	0	1.79	2.18	6.31		
Q12	Helped Understandin	Helped Understanding	No Effect	Helped Understanding	Helped Understanding	Helped Understandin	Helped Understanding	Helped Understanding		
Q13	8.84	6.68	10	9.3	8.41	10	6.6	7.51		
Q14	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8	0
Q15	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8	0
Q16	**Refer below**									
Q17	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Q1 - Subject ID
Q2 - Today's Date
Q3 - Could you see the towing scenarios clearly in the Oculus Rift?
Q4 - Were you wearing corrective lenses?
Q5 - (if "Yes" to Q4))Were you wearing glasses?
Q6 - (if "No" to Q5) Were you wearing contact lenses?
Q7 - (if "No" to Q3) Why do you feel that you could not see the towing scenarios clearly?
Q8 - Did the towing scenes accurately represent towing an F/A-18? (We understand the entire process is not captured. Replicating the entire tow process is out of the scope of this project):
Q9 - Did you have enough time to gain an understanding of your situation and identify potential collision areas for aircraft in each scene?
Q10 - (if "No" to Q9) Which scene(s) did you feel like you did not have enough time allotted to make a decision (select all that apply)?
Q11 - On a scale of 1 to 10 (10 being the most difficult), rate the difficulty of utilizing the AR system: - Slide the marker:
Q12 - What impact did the AR display have on your ability to understand the location of the aircraft in reference to other items (i.e. aircraft, boxes, support equipment) on the flight line?
Q13 - On a scale of 1 to 10 (10 being the most confident), rate your confidence in towing with the AR system? - Slide the marker
Q14 - If a similar AR system was fielded to the fleet and utilized for the towing aircraft, do you think the number of towing-related incidents would decrease?
Q15 - Do you think a similar AR system should be incorporated into the towing process across the fleet?
Q16 - (if "Yes" to Q15) Why do you think a similar AR system should be incorporated into the towing process?
Q17 - (if "No" to Q15) Why do you think a similar AR system should NOT be incorporated into the towing process?

Highlights of Q16 Responses:

"When the sensor lit up when the FA-18 was close to an object, it brought it to your attention and made you focus on that specific area."
"Increased visual accuracy/detail."
"I can see that it would reduce collisions because it is easier to see the edges of the wings. "
"It incorporates visual and audio systems to provide a better understanding of the environment, thereby enabling individuals to make well informed decisions in a timely manner. "



Q11

Quantiles

100.0%	maximum	6.31
99.5%		6.31
97.5%		6.31
90.0%		6.31
75.0%	quartile	4.205
50.0%	median	1.495
25.0%	quartile	0
10.0%		0
2.5%		0
0.5%		0
0.0%	minimum	0

Summary Statistics

Mean	2.045
Std Dev	2.3775978
Std Err Mean	0.8406078
Upper 95% Mean	4.0327215
Lower 95% Mean	0.0572785
N	8

Q12

Frequencies

Level	Count	Prob
Helped Understanding	7	0.87500
No Effect	1	0.12500
Total	8	1.00000

Q13

Quantiles

100.0%	maximum	10
99.5%		10
97.5%		10
90.0%		10
75.0%	quartile	9.825
50.0%	median	8.625
25.0%	quartile	6.8875
10.0%		6.6
2.5%		6.6
0.5%		6.6
0.0%	minimum	6.6

Summary Statistics

Mean	8.4175
Std Dev	1.368615
Std Err Mean	0.4838785
Upper 95% Mean	9.5616908
Lower 95% Mean	7.2733092
N	8

APPENDIX M. PERFORMANCE DATA BLOCKED BY ENVIRONMENT NUMBER AND TYPE

Environment 1

Environment 1 - Hit

	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		100.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Correct	AR Distance	Standard Distance
Standard Distance		12.69		8.38		7.01		11.68	9.36
AR Distance	7.81		10.18		14.53		14.20	AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	6.63	10.00	10.00	10.00	10.00	9.66	8.41	8.76	9.89
Confidence Level Question B	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

Environment 1 - Danger

	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Incorrect		Incorrect		Incorrect	66.67%	25.00%
AR Collision ID		Correct		Correct		Incorrect		AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	10.00	N/A	N/A	8.82	9.34	8.82	9.67
Confidence Level Question B	4.98	10.00	N/A	9.54	1.00	N/A	N/A	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	1.431	1.688	1.746	1.932	1.156	1.454	1.080	9.77	2.99
Speed Std Dev	0.509	0.495	0.490	0.288	0.392	0.538	0.306	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	1.983	2.000	0.982	2.000	0.993	1.003	1.000	1.668	1.239
								AR Speed	Standard Speed
								1.691	1.353
								AR Speed Deviation	Std Speed Deviation
								0.440	0.424

Environment 1 - Caution

	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		100.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Correct	AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	6.74	10.00	10.00	9.88	10.00	10.00	9.50	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	1.731	1.831	1.801	1.791	1.601	1.938	1.647	9.06	9.96
Speed Std Dev	0.456	0.423	0.455	0.469	0.533	0.297	0.487	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	2.000	2.006	1.999	1.999	2.001	1.999	1.999	2.000	2.00
								AR Speed	Standard Speed
								1.70	1.85
								AR Speed Deviation	Std Speed Deviation
								0.48	0.46

Environment 1 - Miss

	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Correct		Correct		Correct	100.00%	100.00%
AR Collision ID		Correct		Correct		Correct		AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	10.00	10.00	10.00	10.00	10.00	9.22	9.56	AR Confidence Q-B	Standard Confidence !-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	9.74	9.89
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

*pilot6 : ATEAR issue discussed in Chapter V.B.2.c

Environment 2

Environment 2 - Hit

	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Correct		Correct		Correct	66.67%	100.00%
AR Collision ID		Incorrect		Correct		Correct		AR Distance	Standard Distance
Standard Distance	16.41		7.57		14.06		17.25	4.95	13.82
AR Distance		0.00		*		9.89		AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	10.00	N/A	10.00	10.00	5.45	7.15	9.14	8.58	8.65
Confidence Level Question B	N/A	8.50	N/A	N/A	N/A	N/A	N/A	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	8.50	N/A
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

Environment 2 - Danger

	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		75.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Incorrect	AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	10.00	10.00	10.00
Confidence Level Question B	8.39	10.00	10.00	10.00	7.70	10.00	N/A	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	1.787	1.821	1.868	1.873	1.570	1.940	1.687	8.69	10.00
Speed Std Dev	0.436	0.420	0.393	0.394	0.527	0.290	0.484	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	1.999	0.805	2.000	1.998	1.900	2.000	2.000	1.975	1.601
								AR Speed	Standard Speed
								1.728	1.878
								AR Speed Deviation	Std Speed Deviation
								0.460	0.368

Environment 2 - Caution

	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		100.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Correct	AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	10.00	10.00	10.00	9.60	10.00	10.00	10.00	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.00	9.87
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

Environment 2 - Miss

	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Correct		Correct		Correct	100.00%	100.00%
AR Collision ID		Correct		Correct		Correct		AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	9.85	10.00	10.00	9.96	10.00	10.00	9.18	AR Confidence Q-B	Standard Confidence !-B
Speed Avg	1.533	1.720	1.852	1.920	1.311	1.166	1.000	9.99	9.76
Speed Std Dev	0.517	0.477	0.392	0.307	0.486	0.395	0.079	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	1.951	1.998	2.001	1.999	2.023	2.006	1.000	2.001	1.744
								AR Speed	Standard Speed
								1.602	1.424
								AR Speed Deviation	Std Speed Deviation
								0.393	0.369

* pilot5 did not let scene finish playback (i.e., no collision triggered)

Environment 3

Environment 3 - Hit

	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		100.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Correct	AR Distance	Standard Distance
Standard Distance		*		12.28		*		5.21	12.28
AR Distance	5.43		5.00		*		*	AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	6.91	10.00	10.00	10.00	7.85	6.88	10.00	8.69	8.96
Confidence Level Question B	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	1.717	1.773	1.811	1.867	1.547	1.832	0.973	N/A	N/A
Speed Std Dev	0.479	0.463	0.458	0.415	0.536	0.424	0.177	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	0.971	0.709	0.823	1.965	0.835	0.973	1.000	0.907	1.216
								AR Speed	Standard Speed
								1.512	1.824
								AR Speed Deviation	Std Speed Deviation
								0.412	0.434

Environment 3 - Danger

	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Correct		Correct		Correct	100.00%	100.00%
AR Collision ID		Correct		Correct		Correct		AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	7.34	10.00	10.00	5.73	8.74	8.15	9.98	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	1.584	1.668	1.773	1.911	1.388	1.298	1.081	7.96	9.01
Speed Std Dev	0.510	0.501	0.462	0.323	0.512	0.484	0.293	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	1.999	1.998	1.993	1.999	2.001	2.001	1.999	1.999	1.998
								AR Speed	Standard Speed
								1.626	1.457
								AR Speed Deviation	Std Speed Deviation
								0.436	0.444

Environment 3 - Caution

	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Correct		Correct		Correct	100.00%	100.00%
AR Collision ID		Correct		Correct		Correct		AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	10.00	10.00	10.00	10.00	10.00	9.95	10.00	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	9.98	10.00
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

Environment 3 - Miss

	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		100.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Correct	AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	10.00	10.00	10.00	10.00	10.00	10.00	10.00	AR Confidence Q-B	Standard Confidence !-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.00	10.00
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

* pilot3 did not let scene finish playback (i.e., no collision triggered)
* pilot6 did not let scene finish playback (i.e., no collision triggered)
* pilot7 did not let scene finish playback (i.e., no collision triggered)
* pilot8 did not let scene finish playback (i.e., no collision triggered)

Environment 4

Environment 4 - Hit

	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Incorrect		Incorrect		Incorrect		75.00%	0.00%
AR Collision ID	Correct		Incorrect		Correct		Correct	AR Distance	Standard Distance
Standard Distance		0.00		0.00		0.00		6.43	0.00
AR Distance	8.83		0.00		*		10.45	AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	6.42	N/A	N/A	N/A	10.00	N/A	10.00	8.81	N/A
Confidence Level Question B	N/A	7.13	10.00	1.00	N/A	4.17	10.00	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.00	4.10
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

Environment 4 - Danger

	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Correct		Correct		Correct	100.00%	100.00%
AR Collision ID		Correct		Correct		Correct		AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	10.00	10.00	10.00	4.14	3.24	8.76	8.98	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.63	8.06
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

Environment 4 - Caution

	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Correct		Correct		Correct	100.00%	100.00%
AR Collision ID		Correct		Correct		Correct		AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	10.00	10.00	10.00	8.17	8.73	10.00	9.93	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	1.659	1.711	1.795	1.911	1.448	1.379	1.190	9.39	9.66
Speed Std Dev	0.500	0.484	0.447	0.320	0.520	0.511	0.401	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	1.998	2.006	2.006	1.549	1.993	2.006	1.917	1.854	1.979
								AR Speed	Standard Speed
								1.667	1.523
								AR Speed Deviation	Std Speed Deviation
								0.438	0.467

Environment 4 - Miss

	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		100.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Correct	AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	10.00	10.00	10.00	10.00	9.67	10.00	10.00	AR Confidence Q-B	Standard Confidence !-B
Speed Avg	1.875	1.802	1.974	1.938	1.871	1.927	1.454	9.92	10.00
Speed Std Dev	0.344	0.422	0.244	0.292	0.374	0.302	0.537	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	2.000	2.000	2.000	1.999	1.999	1.999	2.007	2.001	1.999
								AR Speed	Standard Speed
								1.794	1.889
								AR Speed Deviation	Std Speed Deviation
								0.375	0.339

* pilot6 did not let scene finish playback (i.e., no collision triggered)

Environment 5

Environment 5 - Hit									
	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Incorrect		Incorrect		Incorrect		Incorrect	33.33%	0.00%
AR Collision ID		Incorrect		Incorrect		Correct		AR Distance	Standard Distance
Standard Distance	0.00		0.00		0.00		0.00	2.05	0.00
AR Distance		0.00		0.00		6.14		AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	6.67	N/A	6.67	N/A
Confidence Level Question B	7.35	6.44	10.00	5.59	10.00	N/A	8.45	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	1.611	1.702	1.735	1.909	1.444	1.347	1.168	6.01	8.95
Speed Std Dev	0.515	0.491	0.491	0.330	0.519	0.508	0.381	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	2.120	1.839	1.482	1.998	2.072	1.000	0.938	1.612	1.653
								AR Speed	Standard Speed
								1.653	1.489
								AR Speed Deviation	Std Speed Deviation
								0.443	0.476

Environment 5 - Danger									
	Standard	AR	Standard	AR	Standard	AR	Standard	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID	Correct		Correct		Correct		Incorrect	33.33%	75.00%
AR Collision ID		Correct		Incorrect		Incorrect		AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	9.48	N/A	7.99	8.95	8.73	8.95
Confidence Level Question B	7.44	6.49	10.00	N/A	2.38	N/A	N/A	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	6.49	6.61
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

Environment 5 - Caution									
	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		100.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Correct	AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	9.57	10.00	10.00	10.00	10.00	9.22	10.00	AR Confidence Q-B	Standard Confidence Q-B
Speed Avg	1.831	1.824	1.871	1.948	1.825	1.737	1.229	9.89	9.74
Speed Std Dev	0.389	0.400	0.383	0.282	0.404	0.473	0.451	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	2.000	1.993	2.006	2.001	2.000	2.007	1.982	1.997	2.000
								AR Speed	Standard Speed
								1.689	1.836
								AR Speed Deviation	Std Speed Deviation
								0.406	0.385

Environment 5 - Miss									
	AR	Standard	AR	Standard	AR	Standard	AR	**AR Stats (Avg)**	**Standard Stats (Avg)**
Subject	**pilot2**	**pilot3**	**pilot4**	**pilot5**	**pilot6**	**pilot7**	**pilot8**	AR Correct	Standard Correct
Standard Collision ID		Correct		Correct		Correct		100.00%	100.00%
AR Collision ID	Correct		Correct		Correct		Correct	AR Distance	Standard Distance
Standard Distance								N/A	N/A
AR Distance								AR Confidence Q-A	Standard Confidence Q-A
Confidence Level Question A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Confidence Level Question B	10.00	10.00	10.00	10.00	10.00	10.00	10.00	AR Confidence Q-B	Standard Confidence !-B
Speed Avg	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.00	10.00
Speed Std Dev	N/A	N/A	N/A	N/A	N/A	N/A	N/A	AR Last Known Speed	Standard Last Known Speed
Last Known Speed	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
								AR Speed	Standard Speed
								N/A	N/A
								AR Speed Deviation	Std Speed Deviation
								N/A	N/A

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APPENDIX N. HIT SCENARIO ANALYTICS

Hit Scenarios														
	AR View							Standard View						
Environment	Identification	Distance	Confidence A	Confidence B	Avg Speed	Avg Speed Std Dev	Last Known Speed	Identification	Distance	Confidence A	Confidence B	Avg Speed	Avg Speed Std Dev	Last Known Speed
1	Correct	7.81	6.63	N/A	N/A	N/A	N/A	Correct	12.69	10	N/A	N/A	N/A	N/A
1	Correct	10.18	10	N/A	N/A	N/A	N/A	Correct	8.38	10	N/A	N/A	N/A	N/A
1	Correct	15.53	10	N/A	N/A	N/A	N/A	Correct	7.01	9.66	N/A	N/A	N/A	N/A
1	Correct	14.2	8.41	N/A	N/A	N/A	N/A							
2	Incorrect	N/A	N/A	8.5	N/A	N/A	N/A	Correct	N/A	10	N/A	N/A	N/A	N/A
2	Correct	N/A	10	N/A	N/A	N/A	N/A	Correct	N/A	10	N/A	N/A	N/A	N/A
2	Correct	N/A	7.15	N/A	N/A	N/A	N/A	Correct	N/A	5.45	N/A	N/A	N/A	N/A
2								Correct	N/A	9.14	N/A	N/A	N/A	N/A
3	Correct	5.43	6.91	N/A	1.717	0.479	0.971	Correct	*	10	N/A	1.773	0.463	0.709
3	Correct	5	10	N/A	1.811	0.458	0.823	Correct	12.28	10	N/A	1.867	0.415	1.965
3	Correct	*	7.85	N/A	1.547	0.536	0.835	Correct	*	6.88	N/A	1.832	0.424	0.973
3	Correct	*	10	N/A	0.973	0.177	1							
4	Correct	8.83	6.42	N/A	N/A	N/A	N/A	Incorrect	0	N/A	7.13	N/A	N/A	N/A
4	Incorrect	0	N/A	10	N/A	N/A	N/A	Incorrect	0	N/A	1	N/A	N/A	N/A
4	Correct	*	10	N/A	N/A	N/A	N/A	Incorrect	0	N/A	4.17	N/A	N/A	N/A
4	Correct	10.45	10	N/A	N/A	N/A	N/A							
5	Incorrect	0	N/A	6.44	1.702	0.491	1.839	Incorrect	0	N/A	7.35	1.611	0.515	2.12
5	Incorrect	0	N/A	5.59	1.909	0.33	1.998	Incorrect	0	N/A	10	1.735	0.491	1.482
5	Correct	6.14	6.67	6.67	1.347	0.508	1	Incorrect	0	N/A	10	1.444	0.519	2.072
5								Incorrect	0	N/A	8.45	1.168	0.381	0.938
Overall Averages	0.736842105	6.96	8.57	7.44	1.57	0.43	1.21	0.526315789	3.67	9.11	6.87	1.63	0.46	1.47

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APPENDIX O. DANGER SCENARIO ANALYTICS

Danger Scenarios														
	AR View							Standard View						
Environment	Identification	Distance	Confidence A	Confidence B	Avg Speed	Avg Speed Std Dev	Last Known Speed	Identification	Distance	Confidence A	Confidence B	Avg Speed	Avg Speed Std Dev	Last Known Speed
1	Correct	N/A	N/A	10	1.688	0.495	2	Correct	N/A	N/A	4.98	1.431	0.509	1.983
1	Correct	N/A	N/A	9.54	1.932	0.288	2	Incorrect	N/A	10	N/A	1.746	0.49	0.982
1	Incorrect	N/A	8.82	N/A	1.454	0.538	1.003	Correct	N/A	N/A	N/A	1.156	0.392	0.993
1								Incorrect	N/A	9.34	N/A	1.08	0.306	1
2	Correct	N/A	N/A	8.39	1.787	0.436	1.99	Correct	N/A	N/A	10	1.821	0.42	0.805
2	Correct	N/A	N/A	10	1.868	0.393	2	Correct	N/A	N/A	10	1.873	0.394	1.998
2	Correct	N/A	N/A	7.7	1.57	0.527	1.9	Correct	N/A	N/A	10	1.94	0.29	2
2	Incorrect	N/A	10	N/A	1.687	0.484	2							
3	Correct	N/A	N/A	10	1.668	0.501	1.998	Correct	N/A	N/A	7.34	1.584	0.51	1.999
3	Correct	N/A	N/A	5.73	1.911	0.323	1.99	Correct	N/A	N/A	10	1.773	0.462	1.993
3	Correct	N/A	N/A	8.15	1.298	0.484	2.001	Correct	N/A	N/A	8.74	1.388	0.512	2.001
3								Correct	N/A	N/A	9.98	1.081	0.293	1.99
4	Correct	N/A	N/A	10	N/A	N/A	N/A	Correct	N/A	N/A	10	N/A	N/A	N/A
4	Correct	N/A	N/A	4.14	N/A	N/A	N/A	Correct	N/A	N/A	10	N/A	N/A	N/A
4	Correct	N/A	N/A	8.76	N/A	N/A	N/A	Correct	N/A	N/A	3.24	N/A	N/A	N/A
4								Correct	N/A	N/A	8.98	N/A	N/A	N/A
5	Correct	N/A	N/A	6.49	N/A	N/A	N/A	Correct	N/A	N/A	7.44	N/A	N/A	N/A
5	Incorrect	N/A	9.48	N/A	N/A	N/A	N/A	Correct	N/A	N/A	10	N/A	N/A	N/A
5	Incorrect	N/A	7.99	N/A	N/A	N/A	N/A	Correct	N/A	N/A	2.38	N/A	N/A	N/A
5								Incorrect	N/A	8.95	N/A	N/A	N/A	N/A
Overall Averages	0.631578947	N/A	9.07	8.24	1.69	0.45	1.89	0.842105263	N/A	9.43	8.21	1.53	0.42	1.61

*blue highlight: this is pilot6. Identification manually corrected. Confidence question data removed for this analysis. Refer to Chap V.H.2.c for explanation

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APPENDIX P. SSQ RESULTS

Subject ID	N Before	N After	N Diff	O Before	O After	O Diff	D Before	D After	D Diff	TS Before	TS After	TS Diff
pilot1	28.62	19.08	-9.54	0	7.58	7.58	0	0	0	107	99.71	-7.29
pilot2	0	9.54	9.54	0	15.16	15.16	0	13.92	13.92	0	144.44	144.44
pilot3	0	0	0	0	0	0	0	0	0	0	0	0
pilot4	0	0	0	0	0	0	0	0	0	0	0	0
pilot5	28.62	28.62	0	30.32	30.32	0	27.84	13.92	-13.92	324.56	272.5	-52.06
pilot6	9.54	28.62	19.08	15.16	7.58	-7.58	0	0	0	92.38	135.39	43.01
pilot7	9.54	9.54	0	15.16	22.74	7.58	0	0	0	92.38	120.73	28.35
pilot8	0	0	0	7.58	0	-7.58	0	0	0	28.35	0	-28.35

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