

Human Performance in Cyber-Vulnerable Highly Automated Unmanned Aerial Systems

by

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Abstract

Automation is ever present in today's complex systems of systems. Originally created to ease workload and burden on the human operator and to increase safety by automating dangerous tasks, automation has become practically ubiquitous in almost every human-machine system today. It is present in transportation systems, the industrial complex, and in military applications. While automation is capable of reducing human workload in the human-machine team, and, in some cases, of removing the human from the system all together, it has also been shown to degrade human performance in monitoring and supervising tasks.

In some systems, the supervisory role of the human has shifted from multiple humans monitoring a single system to a single human monitoring multiple systems. Today's increased computing power, optimized algorithms, and machine learning techniques have contributed to the ongoing trend of humans monitoring multiple systems. This may soon be prevalent in military unmanned aerial systems (UAS). These systems use both wired and wireless networks to communicate and to send and receive information to control the system. If not meticulously protected, these systems may be susceptible to cyber intrusions ranging from an adversary monitoring performance to degradation of the system to a point of failure.

Humans rely on timely and appropriate indicators from cyber-physical systems to protect these systems. This dissertation examines human performance during the operation of a generalized UAS control station and user interface. This includes consideration of the impact of disparate operator backgrounds on detecting faults and performance measures when controlling multiple UAS using a common user interface as well as the impact of task loading, in the form of in-the-loop or out-of-the-loop participation. Additionally, the work compares two common UAS control station consoles from an ergonomics perspective, an important issue due to the

prevalence of musculoskeletal disorders among pilots and military personnel and the resultant fatigue and discomfort that could further degrade operator performance in a cyber-compromised environment.

The results of the first study found that the newer ground control station console, MD-4 Mission Control Station (MCS), reduced head-tilt extension angles in upward looking tasks and increased flexion in downward looking tasks resulting in improved lower gaze angles. However, there is still room to improve the postures and gaze angles that must be sustained. The data collection methods and analysis used to compare the two control station consoles could be used to evaluate other existing control stations and inform future ground control station designs for UAS currently being developed.

The second study, which focused on cyber events and their impact on human performance, found that background was significant, with non-gamers worse than both aviators and gamers, while aviator and gamer performance metrics were generally comparable. Regardless of background, cyber events required significantly more time to respond. Task loading further impacted the accuracy of response to cyber events. These results could inform recruitment of future UAS operators focusing on certain experience backgrounds over others. They also highlight the need to further explore cueing of cyber events to operators and a better understanding of cyber events' impact on mission accomplishment. Finally, the research could inform a conversation on the Navy's current requirement for manned flight training for Group 4 and Group 5 UAS operators.

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List of Abbreviations

AIC	Air Interoperability Center
ANOVA	Analysis of Variance
AVO	Air Vehicle Operator
CAC	Common Access Card
CGI	Computer Generated Image
CPS	Cyber Physical System
CRM	Crew Resource Management
DOD	Department of Defense
EMG	Electromyography
FAA	Federal Aviation Administration
FLIR	Forward Looking Infrared
GAO	Government Accountability Office
GCS	Ground Control Station
GPS	Global Positioning System
HCIL	Human Computer Interaction Lab
IBM	International Business Machines
IP	Internet Protocol
ITL	In-the-Loop
KSAO	Knowledge Skills Abilities and Other characteristics
MCS	Mission Control Station
MOCAP	Motion Capture
MSD	Musculoskeletal Disorders

MWA	Mean Weighted Average
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute for Standards and Technology
NSF	National Science Foundation
OMC	Optical Motion Capture
OTL	Out-of-the-Loop
PC	Personal Computer
PMA	Program Management Office
RDT&E	Research Development Testing and Evaluation
ROM	Range of Motion
SPSS	Statistical Package for Social Sciences
TLX	Task Load Index
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UPT	Undergraduate Pilot Training
URT	Undergraduate Remote Pilot Training
USA	United States Army
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy
VPN	Virtual Private Network

VTUAV Vertical Takeoff Landing Tactical Unmanned Aerial Vehicle

Preface

The studies presented in this dissertation were each drafted for publication in leading, relevant professional, peer reviewed journals. The author requests that readers please use the published manuscripts from appropriate journals for the most relevant information and citation purposes.

Chapter III

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Chapter V

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Chapter 1

Introduction

1.1. Background

Automation is ever-present in today's complex system of systems. Originally created to ease workload and burden on the human operator and to increase safety by automating more dangerous jobs, automation is now ubiquitous in most human-machine systems used today. Most of these cyber-physical systems (CPS) require one or more network connections to connect the operator, supervisor, and user interfaces to a system or a series of systems (Yağdereli, Gemci, and Aktaş 2015). The National Science Foundation describes CPSs as those that “integrate sensing, computation, control and networking into physical objects and infrastructure, connecting them to the Internet and to each other.” CPSs “are engineered systems that are built from, and depend upon, the seamless integration of computation and physical components. Advances in CPSs will enable capability, adaptability, scalability, resiliency, safety, security, and usability that will expand the horizons of these critical systems” (NSF n.d.). The National Institute of Standards and Technology (NIST), a part of the U.S. Department of Commerce, defines a CPS as “interacting digital, analog, physical, and human components engineered for function through integrated physics and logic. These systems will provide the foundation of our critical infrastructure, form the basis of emerging and future smart services, and improve our quality of life in many areas” (Thompson 2014). The definition from NIST describes that the human element is an important part of a CPS. The National Science Foundation acknowledges that core research areas include control, autonomy and design, and mixed initiatives such as human-in-the loop or human-on-the-loop, among others.

The automobile industry provides an example. In addition to automatic transmissions, passenger vehicles now regularly come equipped with automated responses to collision avoidance, parking, and near-complete driving autonomy. Moving or dynamic maps receive information from both the vehicle and from outside sources such as global positioning systems and data communications for traffic alerts. In a semiautonomous vehicle, referred to as “high autonomy” by Yağdereli, Gemci and Aktaş (2015), the human can become a pseudo-passenger, with the vehicle executing the preponderance of the work while the human is advised to actively monitor the system and surroundings to ensure safety.

The industrial complex relies heavily on automated processes for regulating production and maintaining safe operating parameters (Edwards 1984). Robotic assembly lines have removed much of the manual labor requirements from humans and have shifted the human’s responsibility to monitoring and supervisory tasks of multiple systems via digital displays and user interfaces (Acemoglu and Restrepo 2017). Workers are often able to monitor indications via a smart device from different locations throughout a facility, and sometimes even remotely with a network connection and login information (Truong and Vu 2012).

In aviation, air vehicles are increasingly complex with incredible performance and technical capabilities. While many private, single-engine aircraft may only require one pilot, many manned aircraft often require more than one operator. In commercial aviation, for example, a minimum of two pilots is often needed to execute the complex array of responsibilities safely. Small unmanned aircraft, commonly referred to as drones, have become readily available to hobbyists while corporations have considered drones for applications such as surveying remote areas for agriculture, utilities, and construction as well as commercial package delivery (Canis 2015; Stolaroff 2014). Regardless of the scenario (i.e., manned vs. unmanned),

technicians may be required to connect diagnostic or calibration equipment to aircraft to perform routine maintenance or to assist in unscheduled troubleshooting. Unmanned aircraft require a network connection to ensure controllability and the sharing of information outside of the platform itself with other platforms. These connections are particularly vulnerable to cyber intrusions that may result in loss of control, spoofing, degraded performance or adversarial monitoring of system parameters for intelligence purposes (Goppert et al. 2014).

The military has invested heavily in aircraft classified as unmanned air systems (UAS). In UAS, humans are removed from the airborne platform entirely. This eliminates physical risk to the human operator, frees up weight and space to add mission systems capabilities, and increases endurance of these platforms. Financial commitments required to research, develop and acquire autonomous and semi-autonomous systems are enormous. The Department of Defense allocated almost \$4.5 billion each year from 2014-2016 for drones, including the MQ-4C Triton, RQ-4 Global Hawk, MQ-8C Fire Scout, MQ-9 Reaper and various undersea and ground vehicles (Gettinger 2017). The Department of Defense may look to capitalize on the ability of a single operator to monitor multiple vehicles. This model, however, is in stark contrast to the traditional model for multi-crew aircraft.

The role of the human operator in the human-machine interaction has shifted heavily to a monitoring or supervisory role of a highly reliable automated system (a system with >99% reliability as discussed by Parasuraman et al. [1993]). This is a role that humans are notoriously poor at performing. Humans easily become distracted and complacent (Parasuraman, Molloy, Robert, and Singh, Indramani 1993; Parasuraman, Mouloua, and Molloy 1996; Bailey and Scerbo 2007; Endsley and Kiris 1995; Endsley 2017). As a result, engineers automate the monitoring of systems to present lights and audible warnings to alert the human of any

degradations or key information. Through this need for automation, we have potentially created two problems for the human in a monitoring role (Endsley and Kiris 1995):

1) Loss of situational awareness by the operator because of reliance on automation –

The human forfeits situational awareness because of the high reliability of the systems and the confidence it instills. Either due to complacency or attention devoted to workload elsewhere, the loss of situational awareness means the human may not have the information needed to make an informed decision or take appropriate action if the system does not perform as expected.

2) Atrophy of skills that may be necessary to respond to unforeseen automated shortcomings or degradations – Because the human has never (or rarely) had to rely on their own abilities, they are not as capable to respond appropriately to unexpected challenges (e.g. evasive action, emergency procedures, etc.). This problem may be further compounded if the operator does not have accurate or necessary information because of the loss of situational awareness.

Naturally, these highly reliable automated systems perform well, in large part because of rapidly improving technology (e.g., computers, software, algorithms, machine learning, etc.). Personal automobile troubleshooting invariably begins with an automated alert display or by having a technician plug in a diagnostic computer to the vehicle. Industrial machines are diagnosed similarly. Through relatively recent advancements, it is easier to monitor industrial system performance. Remote access, in some cases, is available to remotely evaluate system performance. Aircraft, manned and unmanned, are checked similarly to personal automotive vehicles. These systems also use networks, radio and wireless connections while in operation

which could be exploited or compromised. All of these are mentioned to highlight that CPSs can be vulnerable to intrusions.

1.2. Significance

The costs of cyber intrusions on automated systems can be significant. The U.S. Council of Economic Advisors estimated that the cost of cyber-attacks on the U.S. ranged between \$57B and \$109B in 2016. These attacks covered many disparate sectors of the economy and included destruction, disruption, denial of service (DoS), and theft (Council of Economic Advisors 2018). Nonetheless, society is leaning increasingly toward ever-increasing automation with an eye toward full autonomy. Globally, it has been estimated by the Teal Group, that 2018 UAS expenditures of \$4.9B will more than double in ten years to an estimated \$10.7B by 2028 (Teal Group 2018). Similarly, they forecast even greater growth in the civilian unmanned aircraft market from \$4.1B in 2018 to approximately \$13.1B by 2027 (Teal Group 2018).

The U.S. Department of Defense has demonstrated through expenditures a clear desire to expand autonomous systems in its inventory. Sharkey (2011) estimated that the U.S. Air Force, Army, Navy and Marine Corps budgeted almost \$5B towards the development and procurement of unmanned vehicles in 2010. These unmanned systems are used for a variety of missions, to include bomb disposal and surveillance, but large military unmanned vehicles are commonly referred to and recognized as drones (such as the MQ-1 Predator, MQ-8 Fire Scout, and MQ-9 Reaper). While it may be possible to count these larger unmanned systems, the prevalence of unmanned systems is challenging to quantify given the wide proliferation of systems from many countries and the ease of purchasing and modifying commercial off-the-shelf vehicles, as well as the reliance on smaller units for more mundane tasks and missions. For reference, Sharkey

(2011) asserts that there were approximately 150 robots used by the U.S. in 2004 military operations and that number is likely in the thousands now considering all of the different missions unmanned systems can now perform. They are being developed to replace even the newest manned platforms. The X-47B is an unmanned aircraft that is intended to base on naval aircraft carriers ostensibly to replace the newest manned aircraft, the F-35 Lightning, currently coming into the Navy's aircraft inventory (Sharkey 2011). Naturally, by increasing unmanned systems, the number of humans exposed to life threatening hazards is reduced. However, the increased prevalence of unmanned aerial systems has shown at times a greater propensity for mishaps. In 2006, the MQ-1 Predator mishap rate was 32 mishaps per 100,000 flight hours which was significantly more than the manned general aviation mishap rate of 1 per 100,000 hours (Tvaryanas, Thompson, and Constable 2006). Tvaryanas et al. examined 221 UAS mishaps that occurred over a ten-year period from 1994-2003 and found that over 60% were the result of human causal factors.

As fully autonomous systems are developed, improved, and refined, semi-autonomous systems will require operators to make decisions as humans "in-the-loop" that may impact efficiency, productivity, safety, and mission accomplishment. The most notable loss of a UAS was the RQ-170 Sentinel December 2011 to Iran (Yağdereli, Gemci, and Aktaş 2015). The cost of an RQ-170 is not publicly disclosed but it can reasonably be assumed to be a significant number. However, the indirect costs of losing this aircraft in 2011 should not be underestimated as it created a significant public relations problem and eventually (it is assumed) Iran was able to reverse engineer much of the aircraft to create its own version (Opall-Rome 2018).

In the introduction to their 1995 paper entitled *The Out-of-the-Loop Performance Problem and Level of Control in Automation*, Endlsey and Kiris stated "System operators

working with automation have been found to have a diminished ability both to detect system errors and subsequently to perform tasks manually in the face of automation failures, compared with operators who manually perform the same tasks.” They referred to this as the out-of-the-loop performance problem (Endsley and Kiris 1995). For the purposes of this dissertation, an “out-of-the-loop” situation existed when the human operator has not been actively involved in the system inputs and has instead been simply monitoring the system(s). Conversely, an “in-the-loop” situation involved directing a UAS toward its next task and actively participating in the performance of the system such as directing the movements of the vehicles with inputs to heading, altitude, and airspeed. Inputs or interventions occur when the automation encounters something unexpected (Ephrath and Young 1981; Endsley 2017). Interacting with these systems requires trust (Clare, Cummings, and Repenning 2015). The overall system performance of the human-machine system may be affected by the operator’s confidence in the system due to contagion effect(s) of false alarms or unreliable components impacting an operator’s judgement of other true or reliable components (Geels-Blair, Rice, and Schwark 2013). Since human operators oversee autonomous systems in a variety of public and civil enterprises such as power generation and distribution and public transportation, it can be said that human trust or confidence in the system may affect system performance. Beyond the public sector, these results could inform broader government departments, such as the Department of Homeland Security Critical Infrastructure Sectors and the Department of Defense, who in the future envisions multiple autonomous vehicles being controlled by minimal to singular operators (Clare, Cummings, and Repenning 2015).

The amount of data that an automated system is able to process almost certainly exceeds the capacity of a human to observe, internalize and react (Arica, Strandhagen, and Hvolby 2013).

Previous Deputy Defense Secretary Bob Work referred to this as one of our nation's current and future challenges as part of the "Third Offset Strategy" (DoD 2016). Part of this strategy highlighted the critical need not to have better and more capable machines, but rather the need to process the massive amount of associated data and information in order to make it useable for humans in effective and informed decision making. This is the human-machine collaboration challenge. It applies to warnings of imminent failures, attacks, or threats not only to tactical-level units, but also to global networks at large, critical infrastructure, and day-to-day devices that are connected to a network. Humans must rely on timely and appropriate indicators from CPSs that should inform both automated and human responses to protect these systems.

With the human in a supervisory role of multiple systems, the systems are vulnerable to a cyber-event if not meticulously protected. So, how does the human respond to a sudden change in what was thought to be a highly reliable system? More specifically, what if that sudden change does not overtly point to a less reliable system? Instead, gauges, indications and alerts appear to function as intended, but the information they display is not true but rather a manipulated cyber event. To date, research on trust and reliability have focused primarily on either synthetically low reliability systems and how they affect trust or a comparison of high versus low reliability systems and their impact on trust (Parasuraman, Molloy, Robert, and Singh, Indramani 1993). A thorough review of the literature found virtually no research regarding a cyber-attack on system reliability and the subsequent impact on human performance, workload, and trust. How does the human respond or perform when the information before them has been manipulated by a cyber-event of which they may not be aware? Research for this dissertation took a broad approach in attempting to capture some of the impacts of cyber events on human performance in a highly reliable automated system.

In addition to examining human performance specifically in response to cyber events, prudent research should also examine the ergonomic considerations associated with control station designs. The design of ground control stations often involves multiple monitors which may be presented in a variety of arrangements. The design of these workstations may have an important effect on the health and performance of the human operators, particularly in tasks requiring vigilance and change detection.

Musculoskeletal disorders (MSDs) are a significant cause of, and contributor to, injuries resulting in missed work and long-term discomfort. Neck pain has been examined in a variety of ways to include studies on the general population (Sim, Lacey, and Lewis 2006), mobile device users (Ning et al. 2015), office workers (Cagnie et al. 2007), adolescent video gamers (Hakala et al. 2006), military office workers (De Loose et al. 2008), and military aviators (van den Oord et al. 2010). Head and neck positioning must be balanced with eye gaze directionality. Ankrum and Nemeth (1995) discussed how lower gaze angles (below the ear-eye line) are preferred for closer viewing distances (50cm-100cm). As the target moves closer, a lower viewing angle is desired (Ankrum and Nemeth 1995). For reference, assume the distance from an operator to a control station screen is 2.5-3ft (76-91cm.). With one monitor mounted above the other as is common in many ground control stations, the primary way to get a visually comfortable gaze angle on the top monitor is to tilt the head backward until the gaze angle is below the ear-eye line. While accommodating to visual comfort, this results in greater neck extensions which may lead to postural discomfort, and ultimately, MSDs (Ankrum and Nemeth 1995; Kumar 1994).

Despite the absence of specific information about MSDs associated with the two ground control station designs evaluated in this research, MSDs have been identified as a cause for concern among UAS operators as documented by a U.S. Air Force Research Laboratory in 2012.

In a survey of over 1,000 UAS operators to assess health-related behaviors including “reasons for seeking medical care,” researchers asked participants to list conditions aggravated by UAS operations. In addition, they asked participants to self-report any changes to medical services usage, and to describe the reasons for any changes. Finally, they also asked participants to report any changes in the use of alternative health services (chiropractic, massage, etc.) and medicinal usage. Among other self-reported reasons, poor design of work stations resulting in ergonomic strain was cited as a reason for increased medical care usage and musculoskeletal injuries/pain was the leading cause for increased usage of alternative health services (Chappelle et al. 2012). The Air Force Research Lab conducted follow-on research to its 2012 study in 2017. The 2017 data indicated that 52% of the 1,000 UAS operators reported problems associated with video display work such as vision problems and headaches. Additionally, approximately 37% reported MSD problems. These increases among UAS operators were notably higher relative to usage numbers from other specialties in the U.S. Air Force. Increased usage of medical services (both traditional and alternative medicine) as well as prescription medication was similar to the 2012 report, with approximately 15% and 9%, respectively (Chappelle et al. 2017).

A general statement can be made that, of the two different console designs used for this research, one design required greater neck extension to view information on the top screen. This would lead to increased discomfort and/or fatigue while conducting UAS operations. A significant amount of mission-critical information may be located on the top screen, including emergency warnings/alerts, map, payload information, and contact classification interfaces, for example. The location of this information and the nature of the mission tasks require operators to conduct repeated head, neck and eye movements to view the content on both screens. While there is currently no documentation available on specific MSDs associated with this specific user

interface, a revised control station console was developed and is represented by the lower profile console design used in this study.

1.3. Specific Aims

CPSs involve the integration of sensors, computers, instrumentation, controls, and a broader network of systems that may include the human as part of a human-machine system. To function optimally, a CPS must present information in such a way that the human can participate in the system as intended. Robust, reliable automation may afford humans the assistance needed to operate complex CPSs.

Current user interface designs for UAS control stations differ from platform to platform and across military service branches. Not only are the software interfaces different, but the hardware is often substantially different with displays arranged horizontally or vertically, with single-screen and multi-screen vertical, horizontal, and arrayed layouts. Many of those screen arrangements are not conducive to lengthy missions as some head and neck positions cause increased fatigue, soreness, and potentially degraded performance. Examples of two different UAS control station consoles are shown below.



Figure 1: UAS Control Station Examples, U.S. Navy approved for public release.

A common generalized user interface that could be applied across many different types of platforms is advantageous and presumably would result in lower costs and greater interoperability. Simplicity of the user interface is also advantageous. If the design can be made so that training is minimized, then additional costs are saved by providing trained operators at a faster rate. Finally, at the time of this research, the U.S. Navy is the only service that requires designated naval aviators, or manned flight-trained pilots, to operate larger UAS. Other branches such as the U.S. Army and U.S. Air Force have separate qualifications to designate a UAS operator and do not require manned flight training in addition to unmanned aircraft flight training. However, it is not currently fully understood if individuals of disparate backgrounds (e.g., gamers, non-gamers, and pilots) operate UAS systems similarly, if one group performs better than others, or how cyber events impact their performance.

This dissertation is intended to address three specific aims associated with human performance using highly automated, cyber vulnerable UAS:

- Specific Aim #1: Quantify and compare user head-tilt angles associated with neck extension and flexion on two different UAS control station designs while operating a common user interface and simulation scenario.
- Specific Aim #2: Compare user background on participant performance and task load when operating a common user interface given minimal training.
- Specific Aim #3: Compare the effects of in-the-loop or out-of-the-loop tasks on participant performance and task load when operating a common user interface given minimal training.

1.4. Innovation

1.4.1. User Interface and Simulation

A generalized unmanned aerial system and control station user interface created by personnel at Naval Air Systems Command (NAVAIR) Human Systems Engineering Department was used for this research. This system used generalized performance characteristics for surface and air contacts to develop a simulation environment and a control station user interface for multi-asset control and management by a single operator. The interface included functions to manage platform and mission information, navigation control, and payload control of a Forward Looking Infrared (FLIR) camera on all assets.

Vehicle and payload models were created in NAVAIR's Human Computer Interaction Lab (HCIL). Payload images were mid-fidelity representations of systems capabilities, and behaviors were based on unclassified, open source documentation and subject matter expert input. This simplified design allowed researchers and engineers to modify the simulated mission

systems easily. The system design allowed for relatively quick development and testing of user interfaces in a simulation environment with flexibility to apply actual mathematical models of real-world vehicles if needed in the future. The user interface and simulation environment have the potential for quickly testing different locations and modes of information, redundancy of information, and incorporating other sensory cues such as different types of haptics.

Conducting this study from Auburn University using NAVAIR's user interface and simulation environment was accomplished through cooperation between NAVAIR's HCIL, NAVAIR's Research, Development, Test and Evaluation (RDT&E) Air Interoperability Center (AIC) and Auburn University. This cooperation was unique in that the user interface and simulation environment remained housed on NAVAIR servers at Naval Air Station Patuxent River, Maryland. Through coordination with RDT&E AIC, HCIL and Auburn University Engineering Network Services, the lead researcher used a dedicated Internet Protocol (IP) address and point-to-point access to NAVAIR's servers with requisite firewall and network security protections. Utilizing a Virtual Private Network (VPN), the lead researcher, who is also an active Navy member, accessed the simulation environment remotely from Auburn University using Department of Defense (DoD) Common Access Card (CAC) credentials. A schematic showing the basic IT configuration for this is shown as Figure 2.

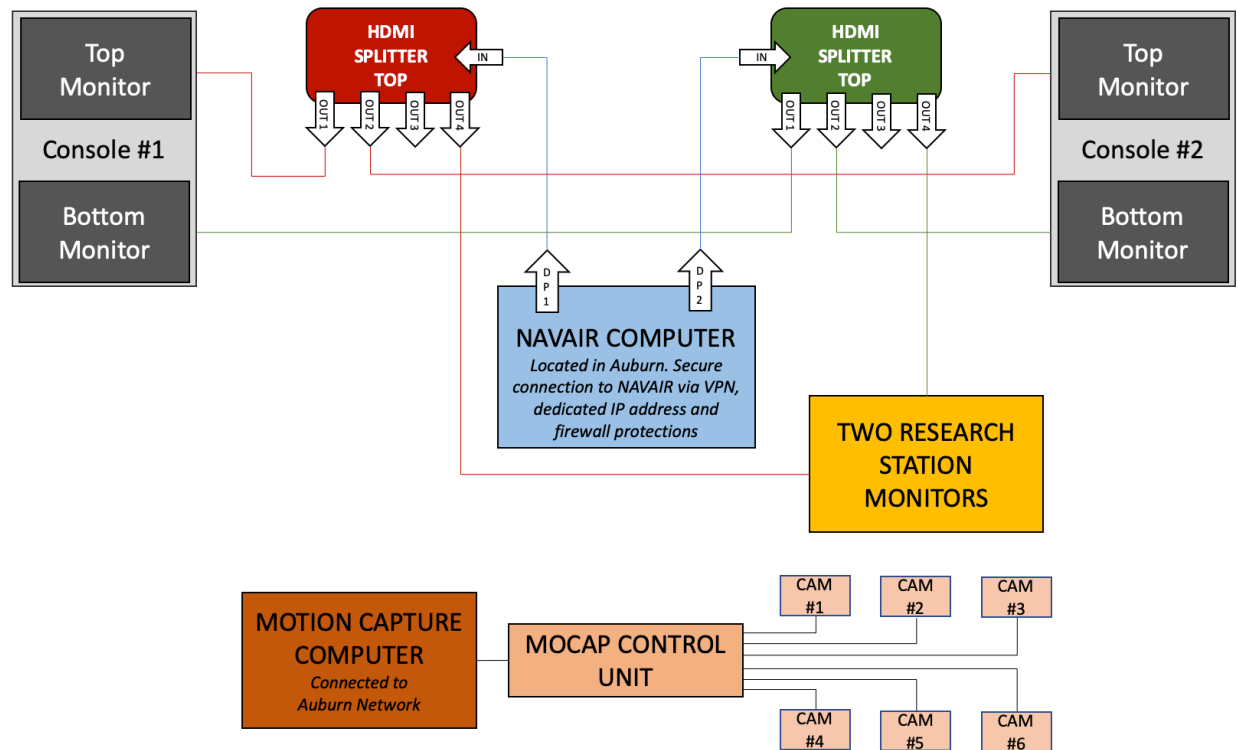


Figure 2: IT configuration for research

1.4.2. Motion Capture System

In support of Specific Aim #1, which involved quantifying and comparing head movements such as neck flexion and extension and head rotation, video optical motion capture (OMC) was used. Marker-based digital OMC is the “gold-standard” for human kinematic and motion analysis (Ceseracciu, Sawacha, and Cobelli, 2014). This is most notably used in human gait analysis as well as other applications such as rehabilitation and development of a life-like, computer generated imaging (CGI).

OMC systems use reflective markers in concert with infrared cameras to collect marker positions in a three-dimensional (3D) environment. With camera positions fixed and known through system calibration, and markers fixed to the subject in a standardized formation, bearing

lines from each camera provide accuracy of marker position to approximately 0.15mm with a variability at 0.015mm (Merriault et al. 2017). These systems passively detect the reflective markers, which are attached to the subject using a double stick tape, Velcro, or affixed to a form-fitting garment. The participant is then able to move virtually uninhibited without wires, cables, or cumbersome sensors.

For this study, a legacy VICON system of six MX-series cameras, one MX Ultranet HD Controller Hardware Unit, a dedicated motion capture personal computer (PC) with Vicon Nexus software (version 1.8.5), and associated cables were used to detect fourteen 12mm markers. Representative images of the system and associated cameras are included below as Figures 3 and 4.

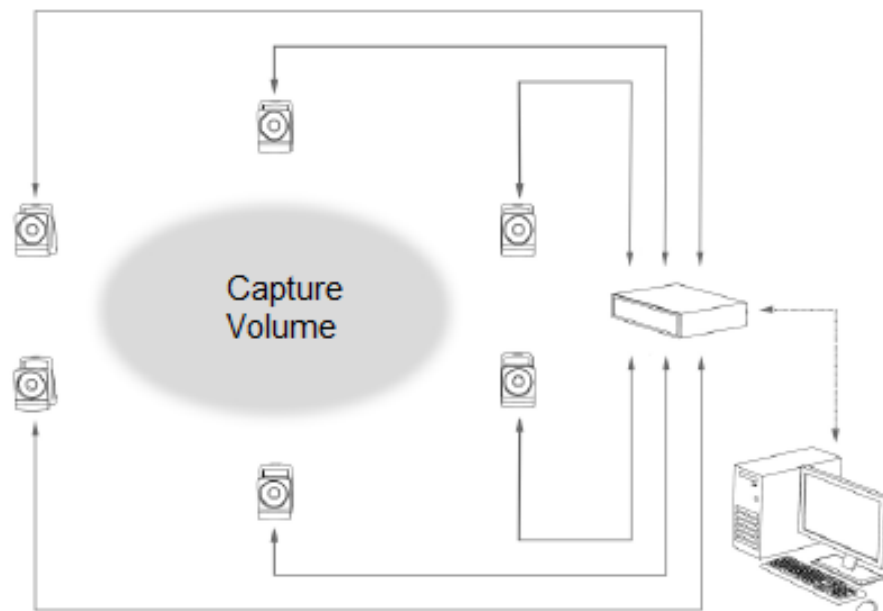


Figure 3: Simple Vicon MX System Architecture Model. (Vicon 2010) Original image modified to reflect six cameras.



Figure 4: Representative image of Victron motion capture cameras used in this research.

The focal of the lenses was 12.5mm while the horizontal width and vertical height of the sensors were 11.20mm and 8.96 mm, respectively (Vicon 2010). These measurements were important in analyzing space options for hosting the research equipment. Despite all information being open source and unclassified, it was determined that due to the connectivity to NAVAIR servers, a secure, single point of entry space was preferred with access controlled by the lead researcher who had the only key. Additionally, access was limited to U.S. citizens only and when accompanied by the lead researcher. This limited the number of available spaces that could host this research and, as a result, a modest corner office with no windows and single keyed entry was selected with the dimensions of approximately 8'x 12'. With the dimensions of the office known and the capture volume influenced primarily by the approximate width of two user control station consoles, it was determined that six cameras were sufficient to provide adequate coverage and redundancy.

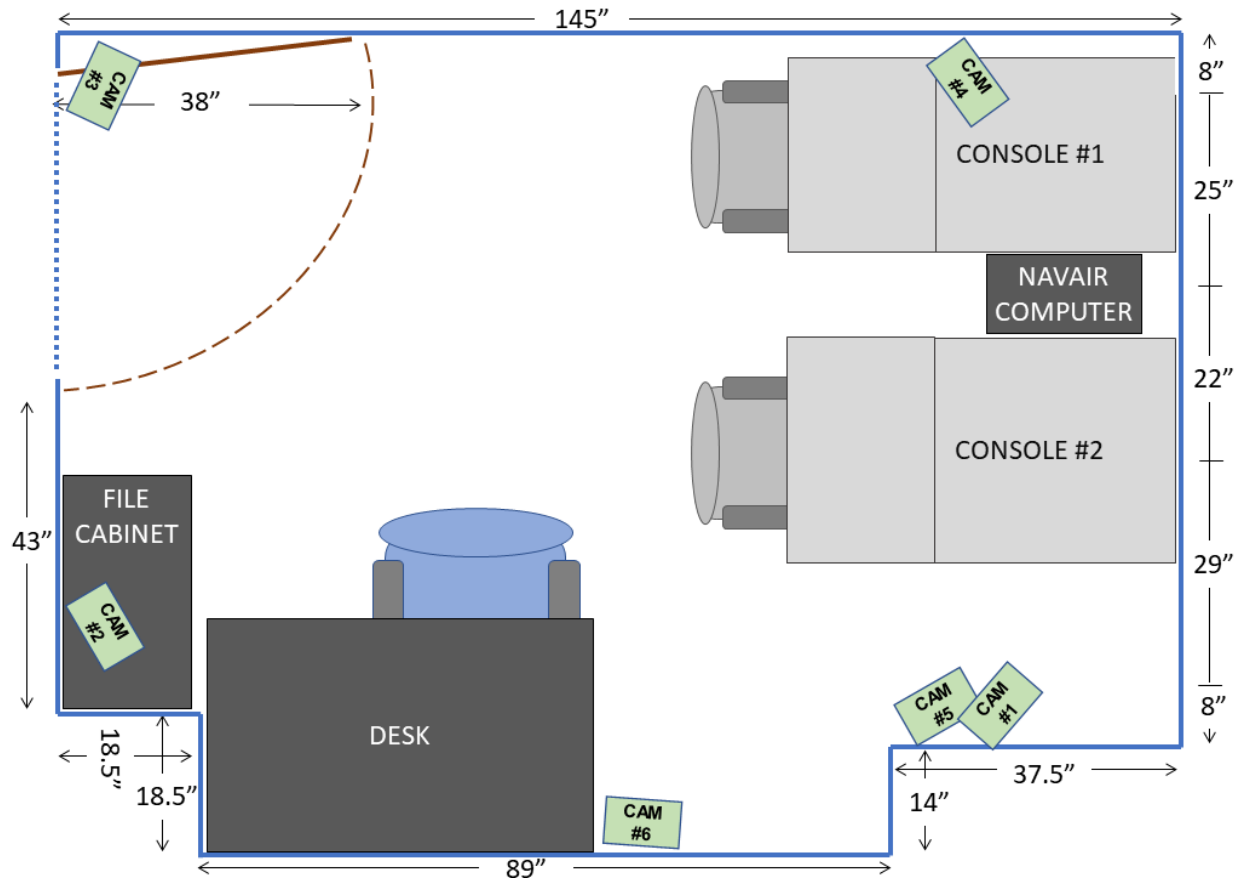


Figure 5: Research Lab located at Auburn University, Woltosz Engineering Research Lab, Rm 2527

A diagram of the lab space used for this research with relative positions of OMC cameras labeled as “CAM #1”, for example, is shown as Figure 5. Cameras #1-4 were mounted near the ceiling at approximately nine feet above the floor and angled at the control station desks. Cameras #5 and #6 were mounted at approximately three and half feet above the floor.

The lab dimensions and depicted OMC camera placement shown in Figure 5 resulted in an approximate capture volume (Figure 6) defined roughly as 2.1m horizontally (H) by 1.3m vertically (V).

Horizontal Field of View (FOV) Width (meters)	Vertical Field of View (FOV) Height V (meters)
$(h) \times (L/f)$	$(v) \times (L/f)$

where:

f = focal length of the lense (mm)

h = horizontal width of sensor (mm)

v = vertical height of sensor (mm)

L = distance from the lense to the object (m)

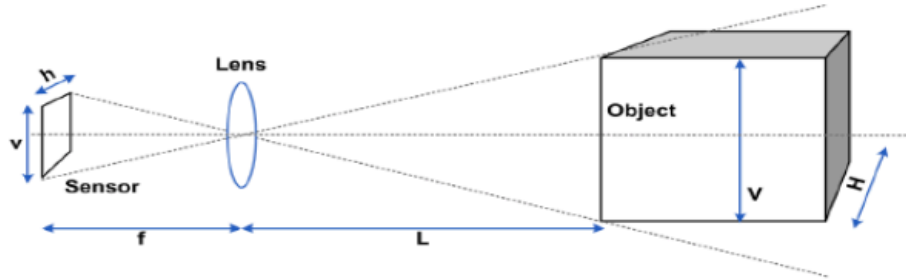


Figure 6: Camera Focal Geometry and Calculations (Vicon 2010)

The marker set used for motion capture was derived from the widely used Plug-In-Gait model marker set that is used in many different biomechanical studies using OMC (Optitrack 2017). The model marker set was truncated to primarily only those markers placed on the upper torso and above. These marker locations were necessitated by the layout of the research space, console(s), and seat design. In addition to the Plug-In-Gait marker set, other markers were added to the tragus and canthus on both sides of the head.

1.5. General Summary

The remaining portions of this dissertation are organized to logically flow through background information, a review of relevant research literature, results of the completed research, discussion of potential policy and training implications of the research, and recommendations on future research. Chapter 2 will explain the literature review process and identified gaps in the literature. Chapters 3 and 4 are devoted to the specific aims outlined previously. The specific aims are intended to address broad considerations for human

performance in operation of a notional UAS control station and user interface. This includes consideration of the control station design as well as the impact of disparate operator backgrounds as well as the effects of task loading, in the form of in-the-loop or out-of-the-loop participation, on detecting faults and other performance measures when controlling multiple UAS using a common user interface. Based on the literature review found in Chapter 2, it was assessed that these are important gaps that should be considered when looking at human performance in a CPS such as a UAS. Chapter 5 focuses on current Navy policies on training requirements for UAS operators and compares those requirements and costs to other military services. Chapter 6 summarizes the overall conclusions of this research and provides recommendations for future research to address outstanding questions and limitations of the completed research.

Chapter 2

Literature Review

2.1. Search Logic

The title of this dissertation, *Human Performance in Highly Automated Cyber Vulnerable Unmanned Aerial Systems*, was searched using the Google scholar, Engineering Village, Aerospace Research Council, and Institute of Electrical and Electronics Engineers (IEEE) databases using the Auburn University library service. With no restrictions on publication type, level of review, language, or date of publication, only the Aerospace Research Council and Google Scholar databases returned results, with 17 and 4,730 links, respectively.

To better use the databases' Boolean search functions, key words were identified and binned according to topic. The topic bins were broken down into five groups or categories: Drone, Trust, Cyber, Security, and Operator. Subsets of keywords that may be commonly used or interchanged were then selected for each of the five categories. For example, "UAS" and "UAV" are often used to describe an Unmanned Aerial System or Unmanned Aerial Vehicle, as is "drone." Likewise, "trust" and "confidence" are often used interchangeably when talking about system reliability and human performance. The subset of keywords was treated with "OR" Boolean logic searches, while the search between categories were treated with "AND" Boolean logic searches within each of the respective academic databases. An asterisk was added to the root search word fragments for each individual search database (as allowable) to further include variations of the root words. For example, instead of simply searching for reliability, a search was completed using *reliab** which would account for different forms of the root word, reliable. Restrictions were placed on the search to limit the results to only Journal Articles, Book Chapters, or Books and those published in the English language. There was no restriction made

on timeframe of publication since it was assumed that the relatively modern topic of unmanned flight would logically present articles to only the past several decades. Any additional restrictions on date of publication were deemed to be unnecessary. A chart showing the Boolean search functions and associated results is shown in Table 1. The resulting numbers of publications are shown as the net number of publications for the corresponding category (and keywords) as well as all the preceding rows of category (and keywords). Naturally, as more “AND” Boolean logic searches are added, one would expect for the results to diminish or stay the same within a database.

Table 1: Boolean Search Logic and Results for Literature Review

Category	Keywords	Results			
		Google Scholar	Engineering Village	Aerospace Research Central	IEEE
Drone	unmanned OR UAS OR UAV OR drone*	888,000	18,310	3,446	2,642
Trust	trust OR reliab* OR vigilan* OR confidence	86,400	1,277	1,732	210
Cyber	cyber physical system OR network	15,300	244	10	78
Security	attack OR intrusion OR threat OR security OR vulnerab*	13,900	66	7	21
Operator	pilot* OR supervis* OR operat* OR monitor*	6,260	30	7	5

The categories and keywords for this search were purposefully broad, while the restrictions were meant to those broad results to only those publications that were reviewed to the highest peer-reviewed standards reasonably possible.

2.2. Publication Screening Process

With a list of articles meeting the search criteria outlined above, the lists of articles from Engineering Village, Aerospace Research Central and IEEE were cross-referenced for duplicate entries. Of the 42 possibilities (30+7+5), it was found that seven articles appeared on one or both

of the other databases, resulting in 35 articles to review. These 35 articles were subsequently screened first by title and then by abstract to determine if they were applicable, resulting in seven that warranted further review. After reading all seven articles, it was determined the seven articles provided applicable background information on cyber threats and vulnerabilities, but none focused on the effects of cyber events on operator performance, which is the focus of this dissertation. The preponderance of these articles focused on network security, health of the unmanned aerial system networks, and the methods that could be used to detect an intrusion and isolate a compromised system(s). The articles provided helpful background on the types of intrusions that are possible or have occurred, but none focused on their impacts on human performance.

As mentioned previously, the initial search was completed using the title of this dissertation, *Human Performance in Highly Automated Cyber Vulnerable Unmanned Aerial Systems*. Of the three databases, Engineering Village, Aerospace Research Central and IEEE, Aerospace Research Central was the only database with any returns providing a list of two publications meeting the same restrictions as used in the broader search (peer reviewed journal, book chapter or book and English language). One of these two was also listed among the 35 articles from the broader Boolean search and was entitled *Analysis and Design of Stealthy Cyber Attacks on Unmanned Aerial Systems* by Kwon, Liu, and Hwang (2014).

As shown in Figure 1, a Boolean search logic was also performed using the Google Scholar database. With over six thousand possible publications returned, it was determined that this number of publications was not feasible for review and Google Scholar does not offer filter functionality for restricting articles to peer-reviewed journals, book chapter, and book as the other databases do. Nonetheless, a review of the first one hundred publication titles resulted in

less than ten articles with potential relevance. Similar to the review of the 35 articles from Engineering Village, Aerospace Research Central, and IEEE, the articles from Google Scholar whose titles were deemed relevant were primarily helpful in acknowledging the vulnerabilities of unmanned aerial systems, but did not highlight any past or current research on the impact of cyber events on operator performance (Hartmann and Giles 2016; Hartmann and Steup 2013; Valavanis and Vachtsevanos 2015; Sampigethaya and Poovendran 2013). A direct search of Google Scholar using the title of this dissertation was also completed. This return resulted in approximately 3,780 returns, many of which were similar to the Boolean search on Google Scholar.

2.3. Gaps in the Literature

This literature review suggests that there is no past or current published research on the effects of cyber events on operator performance in UAS operations. There have been several publications that acknowledge and discuss the vulnerabilities as well as the demonstrated exploitation of these vulnerabilities by adversaries. Several publications focus on how to detect intrusions and network architecture complexities (Sampigethaya and Poovendran 2013; 2012; Goppert et al. 2014). These publications rightfully focus on solutions to acknowledged vulnerabilities. It is not unreasonable to assume that a cyber-intrusion to an unmanned aerial system is undesirable and, therefore, that preventing those events is desirous. However, the purpose of this research was to determine the effects of such an intrusion on the human operator's performance along with other considerations that could impact the operator's performance such as the design and layout of the control station console.

2.4. Publications of Interest

The greatest benefit of the literature review logic and subsequent review of the associated articles was the exposure to other articles that were either linked directly or indirectly to the publications but were not included in the search results. Some of these helped shape the specific aims and design for this research that will be outlined in the next section of this dissertation. These publications include, but are not limited to:

2.4.1. A Study on Cyber-Security of Autonomous and Unmanned Vehicles (Yağdereli, Gemci, and Aktaş 2015)

This paper provides a definition of autonomous, semiautonomous, and unmanned vehicles, to include air, ground and undersea vehicles. It discussed the uses and benefits of autonomy, but also provided case reports of examples where operators over-relied on autonomy and the resulting accidents such as Asiana Flight 214 in July 2013. Yağdereli, Gemci, and Aktaş (2015) categorizes the different types of cyber-attacks as either passive or active. The classic example of passive attack is eavesdropping or intelligence gathering. Active attacks include Denial of Service (DoS), Message modification, Replay or Masquerade. Regarding cyber threats on UAS, Yağdereli, Gemci, and Aktaş (2015) include the following table outlining vulnerabilities and resultant intrusions that could occur on UAS.

Vulnerabilities	Resulting cyber- threat / intrusion
Introduce incorrect input signals (spoofing)	With access to the digital communications network, it becomes possible to trick a controller into an incorrect action by generating erroneous process information. Signal types that may be affected are set points, command functions, interlocks, general data transfers, and system status information. Various defensive mechanisms can be applied to protect the controller at several layers including signal validation.
Generate incorrect output values or commands	In a manner similar to incorrect inputs, erroneous output values can be sent to network connected actuators and other controllers. Various defensive mechanisms can be applied to protect against erroneous outputs including command validation.
Insert messages to indicate incorrect operational status of parts of the system	Messages can be posted for other controllers or corporate networked computers to read that incorrectly indicate the operational status. Such tactics can be used to spoof a maintenance action or force an unnecessary shutdown.
Collect operational information (data, set points)	Simply by tapping into digital data streams, it is possible to determine operating parameters and states that can be used detrimentally by an adversary for more complex cyber-attacks.
Interrupt or corrupt communications between control system components	Rather than directly introducing erroneous process signals for controllers to act on, one can interfere with communications and disrupt the stability of the process. The following failure types may be created depending on the network type and configuration: . Corruption . Incorrect Sequence . Unacceptable Delay . Masquerade . Excessive Jitter . Broadcast Storm (Denial-of-Service of Service) . Babbling Idiot (Commission Fault) . Inconsistency (Byzantine Generals' Problem) . Unintended Repetition . Loss . Insertion . Addressing . Collision
Sender/Receiver related errors	. Buffer Overflow . Incorrect Ordering . Encoding/Decoding . Data Out of Range . Message Too Early
Segmented-network r-related errors	. Very Long Delays in Bridges and Routers . Very Long Times to Initiate Communications . Complete Blockage

Figure 7: Cyber threats to UAS based on exploitation of vulnerabilities (Yağdereli, Gemci, and Aktaş 2015)

The cyber events created and presented in the simulation environment throughout this research were informed by Figure 7, with primary emphasis on “Introduce incorrect input signals (spoofing)”, “Insert message to indicate incorrect operational status of parts of the system” and “Interrupt or corrupt communications between control systems components” vulnerabilities. These were selected due to their relevance to the user interface used in the study and the ability to provide a visible indication that could be detected and corroborated. Additionally, it is believed that the remaining two vulnerabilities are more nuanced and difficult to detect in participants who have not operated the user interface previously. For example, without

experience as a reference, participants may not detect a delay as shown in “Segmented-network related errors.”

2.4.2. Cyber Security Threat Analysis and Modeling of an Unmanned Aerial Vehicle System (Javaid et al. 2012)

This paper presented a model of cyber-threats on UAS. It began with a brief discussion on known, open source reports of successful intrusions or attacks on unmanned aerial systems. In developing their model, Javaid et al. developed a risk evaluation matrix in which *Likelihood of an Event* and *Impact* are rated on a scale of one to three. Likelihood was rated as unlikely (1), possible (2), to likely (3), and impact was rated as low (1), medium (2), and high (3). Risk was calculated as the product of the likelihood and impact values for a given scenario. Minor risk was considered for product values of 1 and 2, Major risk for product values of 3 and 4, and Critical Risk for product values of 6 and 9 (product values of 7 and 8 are not possible since they are not multiples of 1, 2, and 3). A summary of the risk analysis completed by Javaid et al. is shown in Figure 8. The critical risk factors shown (values of 6 and 9), compliment the work done by Yağdereli, Gemci, and Aktaş (2015), and support the development of the simulation cyber events selected for this research.

Threat	Algorithm(s)	Likelihood	Impact	Risk
Jamming		3	1	3
Scrambling/Distortion		2	1	2
Eavesdropping		3	2	6
Cross Layer Attacks		2	1	2
Multi-Protocol Attack		2	1	2
Social Engineering		2	2	4
Spoofing	Device List	3	3	9

	X.509 device Auth.	2	3	6
Command and Control Message Modification (cont'd)	No MAC	3	3	9
	SHA-1 MAC	2	3	6
	AES MAC	1	3	3
Data Traffic Modification	Without AES	3	1	3
	With AES	1	1	1
DoS on UAV/GCS	EAP/SHA-1/AES/MAC	3	3	9
Signal Integrity		3	2	6
Malicious Code, Subroutine Exploit		1	3	3
Virus, Malware, Trojans and Keyloggers		3	2	6

Figure 8: UAS Vulnerability Risk Assessment (Javaid et al. 2012)

2.4.3. From Here to Autonomy: Lessons Learned from Human-Automation Research (Endsley 2017)

This paper highlighted the relationship between the human and the machine. It describes how a human is responsible for supervising and directing an automated system to varying degrees dependent on the level of automation. In order to direct an automated system effectively, a human requires the correct amount of situational awareness to make informed decisions. Insufficient situational awareness by the supervisor or operator will result in suboptimal performance of the human-autonomous machine team. Endsley defines the *Automation Conundrum* as the situation that arises when greater automation is introduced, but the improved reliability and functionality results in lower situational awareness due to overconfidence and/or complacency. Moreover, as system autonomy increases, the human's ability to respond to challenges atrophies because their situational awareness is compromised. Specifically, Endsley points out that improvements to system reliability and performance have the greatest impact on

trust. However, this analysis makes no mention of the severity of the consequences. A key research trajectory that Endsley highlights is the vast amount of work completed to improve human team situational awareness. This has been called Crew Resource Management (CRM) in aviation. However, what is not fully understood is how a human and autonomous system can improve each other's situational awareness as a team. The human-machine team would be enhanced through cooperation and greater situational awareness. However, we must first highlight what could be an emerging issue where information is excessive and could be compromised through a cyber-intrusion.

Endsley's explanation of the *Automation Conundrum* influenced the design of this study, because the control of multiple UAS requires significant, highly reliable automation. These systems are designed to be very robust to deal with a variety of malfunctions and contingencies researched, developed and tested in the acquisition process. However, what if the emergencies or contingencies are not logical, are false, or are not anticipated? What if they were the result of a cyber-event as discussed above? The papers by Endsley (2017), Javaid et al. (2012), and Yağdereli et al. (2015) were the primary drivers for the design of this research.

2.4.4. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research (Hart and Staveland 1988)

This paper provides background on the development of The National Aeronautical Space Administration (NASA) Task Load Index (TLX). The NASA TLX is a subjective workload assessment tool developed to reduce the variability in subjective responses across respondents and across different tasks. It was developed in the 1980s to support US Air Force initiatives related to military aviation but has since been used across many domains in human-machine

interaction. Google Scholar returns over 16,000 hits for NASA-TLX, and the original article discussed here has been cited over 800 times (Hart 2006). The NASA TLX uses six workload factors to assess a user's workload, including: Mental Demand, Physical Demand, Temporal Demand, Own Performance, Frustration, and Effort. These metrics were germane to this study's evaluation of the relevance of experience and backgrounds of participants in operating a user interface.

2.4.5. Foundations for an Empirically Determined Scale of Trust in Automated Systems (Jian, Bisantz, and Drury 2000)

Jian et al. (2000) highlight how, at the time of their research, there had been a significant amount of work completed on evaluating trust. Most of the studies they reviewed revealed the complexity of trust evaluations, both in human-to-human relationships and in human-machine interactions. Human-to-human trust studies have focused on a variety of psychosocial aspects such as honesty, predictability, dependability, and reliability. Human-machine trust studies have similarly looked at predictability, dependability, and reliability, but have also studied complacency of the human as a factor. However, trust evaluations and trust definitions had not been examined to determine if they were the same for human-to-human trust and human-machine trust. With the increasing amount of human-machine teaming, they noted that it was necessary to determine how various models of trust intersect and diverge. Additionally, they demonstrated with empirical data that trust and distrust are negatively correlated. Through survey responses they observed that words associated with trust (confidence, reliability, honesty, etc.) were not correlated with distrust. Similarly, words associated with distrust (suspicion, deception, steal, etc.) were not correlated with trust. Therefore, trust and distrust could be

measured concurrently using high and low-level scales. This was assumed in previous studies. Finally, through cluster analysis of survey results and correlation of words associated with trust and distrust, they observed that humans perceive trust similarly when considering human-to-human and human-machine interaction. Jian et al. (2000) developed an empirically supported scale and survey for assessing trust between humans and automation.

2.4.6. Automation-Induced Complacency for Monitoring Highly Reliable Systems: The Role of Task Complexity, System Experience, and Operator Trust (Bailey and Scerbo 2007)

This study presented two groups of participants, with one group exposed to a high reliability system and the other to a low reliability system. Participants were asked to monitor three tasks and detect deviations. High and low reliability were defined as a 2% and 13% error rate, respectively. Participants were provided an orientation by the researchers to the test apparatus, followed by a five-minute practice session, and then a one-hundred-minute experimental session. This process was completed three times for each participant. A significant correlation was observed between reliability and participant response time in recognizing deviations in parameters, with participants in the high reliability condition displaying greater trust and slower response times. The investigators concluded that highly reliable systems may “severely impair” an operator’s ability to detect unexpected or infrequent events. This paper is important to the present research because the simulated user interface is thought to be highly reliable (>99%), as would be the design for an actual UAS system. However, much like Bailey and Scerbo’s conclusion, cyber events will most certainly be unexpected and/or infrequent and therefore, reduce system reliability.

2.4.7. Performance Consequences of Automation-Induced “Complacency” (Parasuraman, Molloy, Robert, and Singh, Indramani 1993)

In this study, the researchers attempted to determine the impact of automation reliability on participants in a multitask environment. Reliability was artificially set low (56.25%) and high (87.5%) and varied from low-to-high and from high-to-low for random participants. All indications in the system were presented as true, with no false alarms. Each failure was a failure of detection by the automated system. Said another way, every warning light that appeared could be corroborated with a secondary indication. The authors acknowledged the artificiality of the system reliability at 87.5%. A flight system with only 87.5% reliability would not be acceptable and as a result would not be considered highly reliable. While 99% or greater reliability would be more indicative of highly reliable system, they stated that 87.5% was chosen due to time constraints for study purposes. Participants were asked to detect automation failures during four thirty-minute sessions as part of two randomly assigned groups: a constant reliability group or a variable reliability group. Reliability was observed to not affect detection accuracy. However, participants who were presented with variable reliability segments had a higher probability of detection (0.82) compared to those who had constant reliability (0.33), regardless of reliability condition (high vs. low). The authors suggested that their findings supported the concept that taking the operator “out-of-the-loop” of an automated system will degrade their ability to respond effectively due to poorer situational awareness and insufficient manual skill. In another related article, they also pointed out that periodic manual control may improve an operator’s ability to monitor an automated system (Parasuraman, Mouloua, and Molloy 1996).

2.4.8. Adaptive Automation, Trust, and Self-Confidence in Fault Management of Time-Critical Tasks (Moray, Inagaki, and Itoh, 2000)

This study had 30 participants equally divided among various levels of system reliability (100%, 90%, and 70%). Participants were tasked with supervisory control of a representative industrial process in a software environment. They were directed to monitor the system for acceptable operating temperature and system leaks and to take action as appropriate to maintain temperature and/or stop leaks. They could let the automated system continue or interrupt the system if they thought it was necessary to avoid an unnecessary system shutdown. In their findings, Moray et al. indicated that as reliability dropped from 100% to 70%, the probability of accidents increased from 19% to 41%. They concluded that this justified higher automation for fault management.

2.4.9. Influencing Trust for Human-Automation Collaborative Scheduling of Multiple Unmanned Vehicles (Clare, Cummings, and Reppenning 2015)

Clare, Cummings, and Reppenning (2015) studied the effectiveness of priming an operator with information on system reliability ahead of operating the system. Specifically, this study involved gamer (n=18) and non-gamer (n=30) participants tasked with controlling multiple UAVs. Gamers were defined as individuals that played video games daily to a few times a week. Non-gamers were defined as individuals that played video games less than once a month. The primary conclusion of the study was that gamers are more likely to demonstrate over-trust in a system. By priming gamers with the reliability of the system before using the system, researchers were able to improve gamer performance and mitigate their over-trust.

2.4.10. Adaptive Automation for Human Supervision of Multiple Uninhabited Vehicles: Effects on Change Detection, Situation Awareness, and Mental Workload (Parasuraman, Cosenzo, and De Visser 2009)

Parasuraman et al. (2009) evaluated the effects of adaptive automation on human performance in controlling unmanned vehicles. They conducted two studies that required participants to control and/or monitor multiple unmanned vehicles in a simulated contact identification, reconnaissance-type mission. In doing so, participants interacted with simulated air and ground unmanned vehicles, monitored varying levels of communications, and monitored the systems for changes. They found that participant performance in change detection and situational awareness improved for static and adaptive autonomy conditions when compared to manual control. They also found that adaptive autonomy was more beneficial than static autonomy.

2.4.11. 3D Measurement of Cervical and Thoracic Postural Dynamism in Sitting: A Pilot Study (Fourie 2013)

This was a pilot study presented as a Master's thesis in Physiotherapy at Stellenbosch University in South Africa. The primary focus was to demonstrate the use of OMC to measure postural motions in the cervical and thoracic spine while seated at a computer station. The OMC system used in this study was a Vicon motion capture system consisting of eight cameras and the use of the "Plug-In-Gait Model" marker set. Participants were seated in a large open laboratory on a stool in front of a desktop computer. For part of the collection, participants were asked to demonstrate neutral or comfortable position which was recorded as the calibration. The participants were then instructed to perform full range of motion (ROM) movements of the head

and neck (i.e., looking up, down, left and right) and these motions were recorded and analyzed in relation to the self-reported neutral calibration position. Then, the participants were asked to perform a set of six predetermined computer-based tasks. The motion capture system was used to capture the movements associated with those tasks. ROM of the tasks were presented as a true value and as percentage of the full ROM from the calibration. Additionally, the investigators calculated the frequency of movements away from neutral and time spent out of neutral position. One shortcoming of this paper is that neutral position was not specified by parameters but only defined as the “starting position.” It is assumed that the participants obtained a comfortable neutral position looking forward prior to commencing the ROM tasks. However, this cannot be said with certainty. This study demonstrated the utility of OMC for capturing head and neck motions associated with desktop computer work.

2.4.12. Head and Neck Posture at Computer Workstations – What’s Neutral? (Ankrum and Nemeth 2000)

This study provided definitions for neutral or comfortable head and neck postures and compared these postures to different computer monitor heights. The authors point out that many previous studies described neck flexion and extension without defining a baseline neck posture. Similarly, some assessment methods consider neck flexion angles, but do not define the reference point. The authors provide helpful background on the different reference points, lines, and associated angles that have been used in the human factors and ergonomics community to define neck flexion and extension. Some of these include the ear-eye line defined as the line between the cartilage protrusion in front of the ear opening and the outer slit of the eyelid, called the tragus and canthus, respectively. Head-and-neck posture was defined as the angle between

the vertical plane and the line between the tragus to the C7 vertebra. Head tilt was the angle between the ear-eye line and the horizontal plane. All values were determined by using video analysis software. This data can be collected for the purposes of the present study by including markers on the tragus and canthus on each side of the head. These markers may be incorporated with head and upper torso markers of the previously mentioned Plug-In-Gait model marker set to provide a wealth of precise data. Other papers have used similar markers to discuss monitor placement and head/neck positions. However, these studies did not use a gold standard OMC system as was used for this current research.

2.4.13. Effects of Computer Monitor Viewing Angle and Related Factors on Strain, Performance, and Preference Outcomes (Sommerich, Joines, and Psihogios 2001)

In their study, Sommerich et al. (2001) highlighted that studies have shown that high monitors are known to cause visual stress while low monitors may be better for visual stress but may cause musculoskeletal effects. Visual stress associated with high monitors is increased with shorter viewing distances. They included in their paper a conceptual monitor placement strain model, shown below as Figure 9, based on a high monitor at eye level and low monitor at 45° below eye level. This model shows some of the hazards associated with monitor placement and is helpful in understanding the pros and cons each monitor placement.

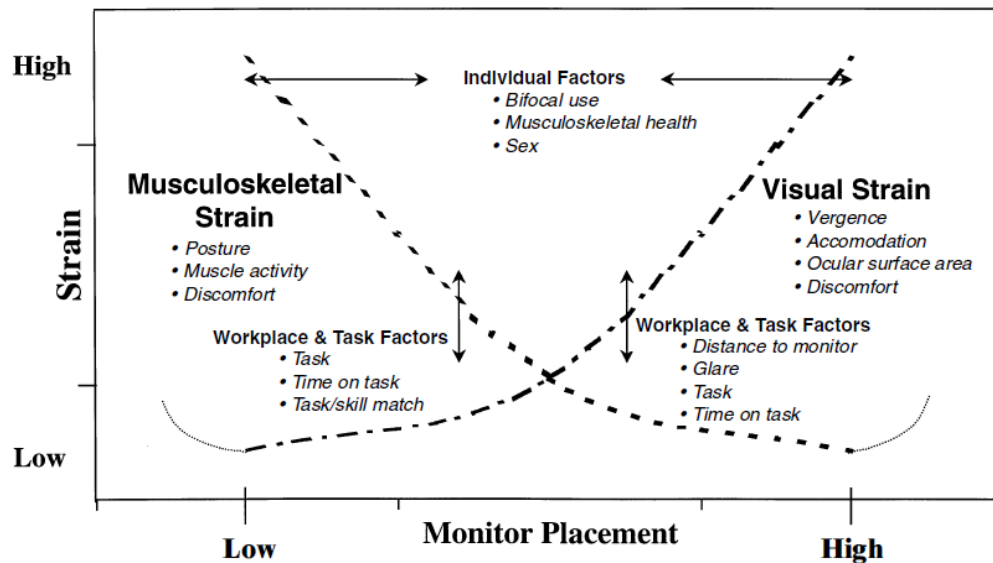


Figure 9: Conceptual monitor placement strain model (Sommerich, Joines, and Psihogios 2001)

To quantify their strain model, they used electromyography (EMG) to measure muscle activity and conducted qualitative surveys. They found that viewing angle greatly impacted muscle activity, performance and preference. (Sommerich, Joines, and Psihogios 2001)

2.4.14. Operator Selection for Unmanned Aerial Vehicle Operators: A Comparison of Video Game Players and Manned Aircraft Pilots (McKinley et al. 2009)

This study was conducted in support of the U.S. Air Force in response to increased UAS operations and the need for more UAS operators to meet rapidly expanding UAS missions. As they highlighted in their study, UAS ground control stations use traditional desktop computer and gaming devices that creates a game-like feel to the workstation. As a result, they explored the background and use of gamers as UAS operators. McKinley et al (2009) also highlighted previous research suggesting that non-pilot gamers could be trained to be just as capable as trained pilots in UAS operations and that gamers have faster reaction times than non-gamers.

The researchers compared the performance of video game players and pilots completing cognitive tasks used previously in related studies such as the Cambridge Neuropsychological Assessment Battery (CONTAB) and Multi-Attribute Task Battery (MAT-B). The cognitive skills they evaluated included but were not limited to situational awareness, timing, motor control and coordination, memory, multitasking and spatial awareness (McKinley et al. 2009). Pilots performed appreciably better than gamers on multitasking cognitive tests, while gamers performed better than pilots on tasks related to finding and tracking targets. Perhaps surprisingly, pilots and gamers did not perform statistically significantly different for UAS landing tasks. Based on their results, researchers concluded that gaming experience may be a desirable skill for UAS operators and that training operators with gaming experience could help reduce training time (McKinley et al. 2009).

2.4.15. The Effects of Commercial Video Game Playing: A Comparison of Skills and Abilities for the Predator UAV (Triplett 2008)

In his 2008 thesis at the U.S. Air Force Institute of Technology, Triplett analyzed the skills intrinsic to video game play to those required for Predator (US Air Force MQ-1 UAS) unmanned aircraft operations (Triplett 2008). He provided a list of overlapping skills observed and concluded that gamers could be viable candidates for UAS operators. Triplett made a critical point regarding basic flight experience. He pointed out that due to the lack of haptic feedback, motion, and the significant presence of automation, UAS operators needed basic flight background to better interact and interpret the system. This background would help their decision-making and thought processes by understanding the performance of the aircraft and the time associated with inputs to the aircraft and the resulting response. When he looked at the

skills of the gamers and pilots, he found that the greatest discrepancy was in flight system knowledge and aircraft characteristics. Depending on the level of automation, an understanding of both of these may be critical to comprehending large amounts of information presented on UAS control station displays.

2.4.16. Video Game Experience and Gender as Predictors of Performance and Stress During Supervisory Control of Multiple Unmanned Aerial Vehicles (Lin et al. 2015)

Lin et al (2015) evaluated if gender and gaming experience represented potential solutions for manning shortfalls anticipated with increased UAS operations. Varying workload and levels of automation, Lin's team found that both men and women gamers were viable candidates to be UAS operators. Gender was not significant. In particular, they highlighted that gamers relied on automation to a greater extent than pilots in higher workload conditions and during performance of a simulated weapons release task resulting in lower stress. Additionally, they found that gamers with significant ("significant" was not clearly defined) self-reported first-person shooter and action gaming expertise were more accurate in the evaluated weapons release tasks (Lin et al. 2015).

2.4.17. Operator Qualification Differences between Manned and Unmanned Aerial System (UAS) (Pagan, Astwood, and Phillips 2014)

This study examined the overlap and differences of qualifications associated with UAS and manned flight operations. To do this, they compiled and compared a list of Knowledge, Skills, Abilities, and Other personal characteristics (KSAOs) for each group, manned and unmanned. They found that approximately 90% of the manned flight most critical KSAOs overlapped with

unmanned KSAOs. However, they were careful to point out that quantity of critical or important KSAOs for each group was different, with 67 important manned KSAOs and 42 important unmanned KSAOs (Pagan, Astwood, and Phillips 2014). Skills identified by Pagan et al. (2014) as not used for UAS operators included, among others, psychomotor skills, motivation, spatial orientation and mental rotation. As a result, they proposed that the primary manned flight skills of naval aviators tasked with flying UAS may be underutilized. This could result in the aviator becoming complacent or bored, and/or have less job satisfaction when operating UAS. Pagan et al (2014) concluded that manned aviators may not be the optimal solution to filling UAS operator positions and that not using some critical skills inherent in manned flight may negatively affect manned flight-trained operator performance in UAS operations.

Chapter 3

Impact of Workstation Design on Head-Tilt Angles: An Evaluation of Two Unmanned Aerial System Control Station Consoles

3.1. Introduction

Today, with computer monitors relatively affordable and offered at exceptionally high resolution, it is not uncommon for people at work or at home to have multiple monitors to increase productivity and display surface area. The expanding use of personal and work desktop computers has necessitated an increase in research on computer monitor positioning as the arrangement of computer monitors present tradeoffs for musculoskeletal comfort and eye strain. Positioning a monitor below eye-level provides users with more options in finding comfortable head and neck postures without impacting vision (Ankrum and Nemeth, 1995). Burgess-Limerick et al. (1999) examined the benefit of eye-height monitor placements relative to monitor positions below eye-height. Results of their study indicated that positioning a monitor 18 degrees below eye level did not have an appreciable impact on head/neck positions in relation to the trunk, but the lower position brought gaze angles down to more closely align with preferred look down angles of 15° and 35° below the ear-eye line as previously proposed by Ankrum and Nemeth (1995) and Hill and Kroemer (1986), respectively. Burgess-Limerick et al. (1999) concluded that the lower monitor positions allowed participants to compromise and find a balance between visual and musculoskeletal comfort.

To properly examine and compare head/neck positions for different displays, a common understanding of a neutral position must be known, thus allowing a comparison of deviations from neutral. Ankrum and Nemeth (2000) focused on establishing and defining the “neutral

position” when using monitors in order to compare different postures. As described in their paper, several earlier studies used benchmarks or limits for flexion and extension but did so without providing a neutral or “zero point” from which to measure the flexion or extension angle. In other studies, neutral position was defined in a variety of ways that may have involved standing and different visual targets that do not align with seated desktop workstation evaluations. With a neutral position defined, observed changes in posture in relation to neutral position are possible. The angles used by Ankrum and Nemeth (2000) to establish the neutral position were the head-tilt angle and the head-neck angle. The head-tilt angle was defined as the angle formed by the ear-eye line, or the straight line connecting the point adjacent to the outer slit of the eye called the canthus and the point of cartilage that sticks out in front of the ear opening called the tragus, relative to the horizontal plane. The head-neck angle was defined as the angle formed by the line extending from the tragus to the seventh cervical vertebra (C7) and a vertical line running through C7. Participants wore a marker on C7 and moved through a range of motions that included looking side-to-side and front-to-back while being filmed. Participants were then asked to find the “most comfortable” position which was their personal “neutral” position. The mean neutral head tilt position was found to be 7.7° above horizontal and the mean comfortable head/neck angle was 43.7° forward of vertical.

Downward gaze angles are less stressful on ocular muscles and have been shown to reduce eye strain, fatigue, headaches, etc. when the distance to different monitors is comparable. However, as a monitor is moved closer along a fixed gaze angle, visual strain will increase. Jaschinski-Kruza (1991) showed that visual strain is greater with a monitor 50cm away when compared to a monitor placed 100cm away (Jaschinski-kruza 1991). The implication is that users must increase extension or decrease flexion angles of the head/neck in order for the eye gaze

angle to adjust to the preferred look down angles discussed above. In contrast to the studies previously discussed, Turville et al. (1998) evaluated monitors placed at 15° and 40° below eye level and did not find evidence that lower monitor placement improved the “health and safety of the operator.” Using EMG, they also found that muscle activity was higher for the participants when looking at the monitor 40° below eye level. Sommerich et al. (2001) modeled the effects of monitor placement at three different vertical positions (0°, -17.5° and -35° to the center of the screen) to evaluate the interaction of monitor placement on musculoskeletal and visual strain. Their results suggested that each position offered different benefits, but the -17.5° position was most advantageous. Subjective preference also identified the -17.5° position as the best (Sommerich, Joines, and Psihogios 2001). Additionally, placing monitors at lower positions to reduce eye strain will cause greater muscle activity about the seventh cervical vertebrae. To counter the weight of the head positioned forward, anterior muscles that support the neck such as the Cervical Erector Spinae and Thoracic Erector Spinae extend to counter the head and neck segment flexion (Turville et al. 1998). It was proposed that “there is probably no ideal placement that simultaneously minimizes musculoskeletal and visual strains, but there may be a location, or zone, in which both can be reasonably low” (Sommerich et al., 2001, pg. 41).

Like many commercial and private desktop applications, the military has numerous workstation applications designed to include multiple monitors for increased efficiency and the display of a large amount of information. These workstations must be designed with extreme and harsh environments in mind and are often constrained by space and footprint. In particular, the military has invested heavily in UAS as removal of the aviator from the system eliminates physical risk to the aviator, frees up weight and space to add mission systems capabilities, and increases the endurance of the platforms. Financial commitments to research, develop and

acquire autonomous and semi-autonomous systems are enormous. The Department of Defense allocated almost \$4.5 billion each year from 2014-2016 for unmanned vehicles and associated technology. With highly reliable, semiautonomous vehicles, single operators may, in some cases, be able to monitor multiple UAS. Controlling and monitoring multiple UAS requires a significant amount of information to be displayed and available to the operator. This is often accomplished on multi-monitor displays that may be arranged in a variety of formats depending on the design specifications of the system. As an example, the ground control station for the MQ-8 Fire Scout used by the U.S. Navy and other military organizations is oriented with two monitors stacked vertically. While functional, the initial console design, known as the Vertical Take-Off and Landing Tactical Unmanned Aerial Vehicle (VTUAV) Ground Control Station (GCS), resulted in many complaints from operators due to neck pain and fatigue associated with sustained postures requiring looking above horizontal. As a result, the Navy redesigned the console, lowering both monitors and adjusting their tilt. This redesign, known as the MD-4 MCS, resulted in less complaints and was believed to be a suitable solution. No study systematically compared the two designs, however, to determine if the newer, alternative MD-4 MCS led to statistically significant improvements in head-tilt angles relative to the VTUAV GCS. The objective of this study was to evaluate if the MD-4 MCS console provided statistically significantly more neutral head-tilt angles for most screen monitoring tasks relative to the legacy VTUAV GCS console.

3.2. Methods

3.2.1. Participants

Twenty participants (ten male) recruited from the Auburn University community participated in this study. Inclusion criteria included being/having: 1) a US Citizen; 2) 19-42 years of age; 3) corrected visual acuity of 20/20; 4) color vision; 5) no history of a physician-diagnosed neck/shoulder or lower back injury; 6) absence of neck/shoulder or lower back pain during the previous 14 days. The citizenship requirement was due to the nature of the study that is supporting U.S. Navy interests. The age requirement was meant to reflect the potential age range of those who serve in the military, while 19 years old was imposed by Alabama State law as the minimum age for an adult to consent to participate in a research study. Visual acuity and color vision requirements were to mirror those set by the U.S. Navy for those who fly aircraft. Finally, while the protocol performed by the participants was not arduous by any means, it was prudent to restrict those with any neck, shoulder, lower back injuries or pain from participate so that their motions and postures did not affect the results.

3.2.2. UAS Control Stations and User Interface

Current user interface designs for UAS control stations differ from platform to platform and across military service branches. Not only are the software interfaces different, but the hardware is often substantially different with single screen and multi-screen options available in various configurations. A generalized user interface that could be applied across many different types of platforms is advantageous and presumably would result in lower costs and increased interoperability. Simplicity of the user interface is also advantageous. If the design can be made so that training is minimized, then additional cost savings could be realized by providing trained

operators at a faster rate. Additionally, due to space restrictions on existing Navy shipboard platforms, arranging the monitors vertically allows for a smaller floor footprint and is in line with other display consoles used by the Navy in Combat Information Centers. This study was conducted using to-scale mock UAS control station consoles constructed following designs currently used by the U.S. Navy (Table 2, Figure 10).

The console designs differ primarily in overall height, with the newer, MD-4 MCS design having its monitors lower in comparison to the VTUAV GSC. Angles of the monitors were slightly different as well with the MD-4 MCS top monitor angled down more vertically. A design eye height of 49 inches was the same for both consoles and the monitor size of 24 inches was used for both as well. Additional dimensions are included in Table 1 below.

Table 2: Dimensions of the control station consoles. The legacy console was the Vertical Take-Off and Landing Tactical Unmanned Aerial Vehicle (VTUAV) Ground Control Station (GCS). The newer design was the MD-4 Mission Control Station (MCS).

	VTUAV GCS	MD-4 MCS
Height	75.5 inches	68.4 inches
Width	29.0 inches	29.5 inches
Display Size	24-inch monitor (x2)	24-inch monitor (x2)
Design Eye Position	49.0 inches	49.0 inches
Height to Top of Top Monitor	66.5 inches	61.5 inches
Height to Top of Bottom Monitor	50.5 inches	45.5 inches
Angle of Top Monitor	22 degrees (top toward)	8 degrees (top toward)
Angle of Bottom Monitor	8 degrees (top away)	18 degrees (top away)
Desktop Height	31.0 inches	29.0 inches

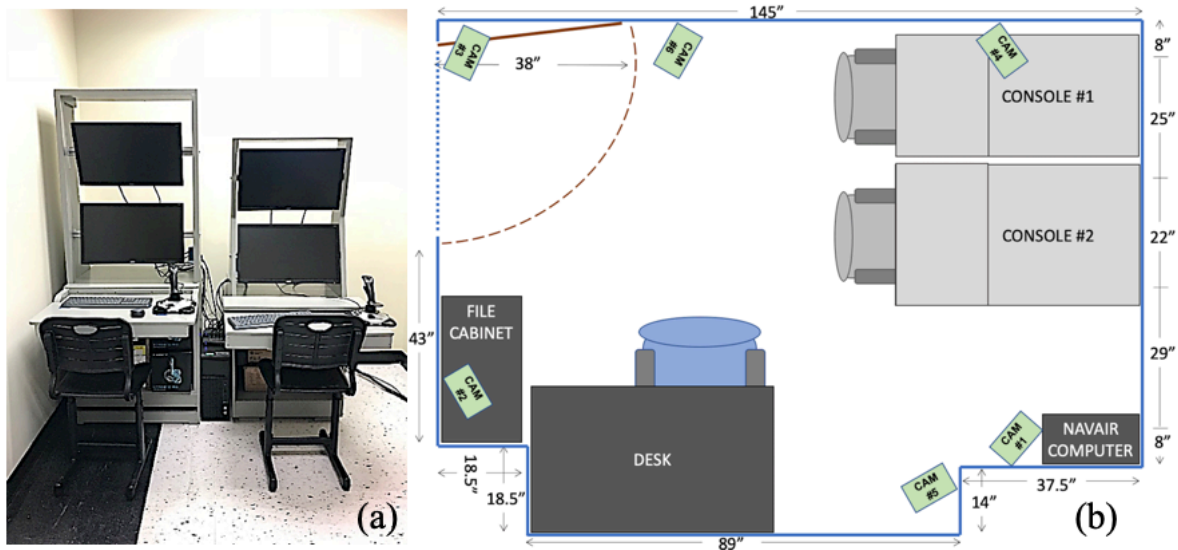


Figure 10: (a) UAS control station consoles used in this study, representative of some of those used by the U.S. Navy. Left console is the VTUAV GSC and the right console is the MD-4 MCS. (b) Arrangement of motion capture cameras in relation to control station consoles in the lab setting.

A generalized unmanned aerial system and control station user interface created by personnel at Naval Air Systems Command (NAVAIR) Human Systems Department (4.6) was used in this study. This system used generalized performance characteristics for surface and air contacts to develop a simulation environment and control station user interface for multi-asset control and management by a single operator. The interface included functions to manage platform and mission information, navigation control, payload control of a Forward Looking Infrared (FLIR) camera on all assets, and map and radar information.

Vehicle and payload models were created in NAVAIR's Human Computer Interaction Lab (HCIL). Systems capabilities and behaviors were based on unclassified, open-source documentation and subject matter expert input. This simplified design allowed researchers and engineers to modify the simulated, notional mission systems easily as well as relatively quick

testing of user interfaces in a simulation environment with potential for applying actual mathematical models of real-world vehicles if needed in the future.

The top screen housed three display areas, including: a Payload Display (or camera view), a Map Display, and an Alert Information Display. When activated, a visual banner illuminated across the top of the top screen to alert the user of a system degradation. For this banner, participants were instructed to click on the banner to suppress its appearance.

The bottom screen housed five display areas: System Status display, Flight Control Display, Photo Library Display, Orientation Display, and Chat Window. The System Status Display housed digital gauges for up to two UAS at a time. Participants could select which vehicles via a dropdown menu. The gauges included a variety of vehicle systems such as Fuel Quantity, Fuel Pressure, Oil Temperature, Oil Pressure, Battery Charge, Link and GPS Status. The Flight Control Display was where participants could enter and adjust Airspeed, Heading or Altitude for a vehicle. The Flight Control Display allowed input to one vehicle at a time. Inputs to multiple vehicles had to be completed individually by selecting the appropriate vehicle via a dropdown menu on the Flight Control Display. The Photo Library Display showed all pictures taken with the onboard cameras from all four UAS. The Orientation Display showed five digital gauges familiar to those with an aviation background. These were an attitude gyro, heading indicator, speed indicator, radar altimeter, and vertical speed indicator. The Orientation Display allowed participants to monitor a second vehicle's parameters via gauges in addition to those parameters shown in the Flight Control Display. Finally, the chat window was a running dialogue with the participant and the simulated mission controller. The interface provided pre-scripted chat messages from the mission controller that the participant could read and respond to as necessary.

Prior to data collection, participants were briefed by the researcher on the different functions of the user interface. Participants were prepared to perform routine computer and gaming functions associated with the user interface and simulation environment by operating a joystick, keyboard, and mouse. All of the participants in this study participated previously in a separate study that assessed their performance in operating the user interface in a simulation environment over an extended period of time. Thus, participants were familiar with the functionality and the briefing by the researcher primarily served as a reminder.

3.2.3. Data Collection and Experiment

Marker-based OMC is the “gold-standard” for human kinematic and motion analysis (Ceseracciu, Sawacha, and Cobelli 2014). OMC is most notably used in human gait analysis as well as other applications such as rehabilitation and development of computer-generated images (CGI). OMC systems use reflective markers in concert with infrared cameras to collect marker positions in a three-dimensional (3D) environment. With camera positions fixed and known through system calibration, and markers fixed to the subject in a standardized formation, bearing lines from each camera provide accuracy of marker position to approximately 0.15mm with a variability at 0.015mm.

Most of the previous workstation studies mentioned in this paper used video analysis of participant positions. For this study, a VICON system of six MX-series cameras, one MX Ultranet HD Controller Hardware Unit, a dedicated motion capture personal computer (PC) with Vicon Nexus software (version 1.8.5), and associated cables were used to detect thirteen 12mm markers. Motion capture cameras #1-4 were mounted near the ceiling at approximately nine feet above the floor and angled at the control station desks. Camera #5 was mounted approximately

two and half feet off the floor and camera #6 was mounted at approximately three and half feet above the floor. The lab dimensions and camera placement resulted in an approximate capture volume defined roughly as 2.1m horizontally (H) by 1.3m vertically (V). The console that was being evaluated was positioned in the center of the capture value for each collection.

The marker set used for motion capture was derived from the widely used Plug-In-Gait model marker set that is used in many different biomechanical studies using OMC. The model marker set was truncated to only those markers placed on the shoulders and above. These marker locations were necessitated by the layout of the research space, console(s), and seat design. In addition to the Plug-In-Gait marker set, other markers were added to the tragus and canthus on both sides of the head to align with data collected by Ankrum (2000) and Burgess-Limerick (1999). The markers and descriptions are provided in Figure 11 and Table 3.

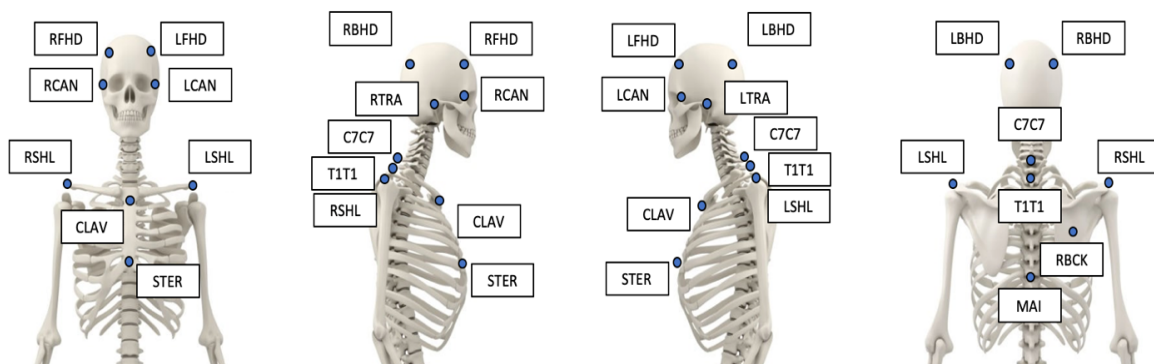


Figure 11: Location of optical motion capture markers derived from Plug-In-Gait Model marker set and points of interests outlined in head/neck angle studies for monitor placement.

Table 3: Description of optical motion capture marker location derived from Plug-In-Gait Model marker set and points of interests outlined in head/neck angle studies for monitor placement.

LABELS	ANATOMICAL LOCATION	PLACEMENT DESCRIPTION
Head Markers		
LFHD	Left Anterior Head	Place the markers on the left and right side of the forehead.
RFHD	Right Anterior Head	
LBHD	Left Posterior head	Place the markers on the left and right side of the head approximately 2 cm behind the ear.
RBHD	Right Posterior head	
Torso Markers		
STER	Xiphoid Process	Bottom most section of the sternum. Place the marker at the bump of the xiphoid process.
CLAV	Manubrim	Located at the top of the sternum. Also called the handle. Place the marker on the center of the two clavicle bones.
C7C7	7 th Cervical Spine Vertebra	The largest vertebra located at the most inferior region of the neck. This section usually protrudes to the posterior side.
T1T1	First Thoracic Vertebra	Large vertebra located just below the C7 vertebra.
MAI	T8 Vertebra	Count 8 vertebra down from C7 or approximate by lining up with the inferior point of the shoulder blades.
RBCK	Middle of Right Shoulder Blade	Reference marker for OCM since the marker set is otherwise symmetrical.
Facial Markers		
RCAN	Right Canthus	The point on the side of the face adjacent to the eye slit opening.
LCAN	Left Canthus	
RTRA	Right Tragus	The point on the side of the face defined by the cartilage that protrudes in front of the ear opening.
LTRA	Left Tragus	

After placing the markers on each participant, seat height was set for all participants so that eye height was 49 inches from the floor. This height was set to be consistent with the original design of the consoles and was meant to mitigate gender and/or anthropometry

differences. The seats used for this study could be adjusted vertically but did not allow for pivot or swiveling. No adjustments or movement of the chair were completed by the research team after setting the eye height at 49 inches. A static calibration of each participant was collected to support data collection. Participants were then directed to perform specific tasks that were recorded with the OMC system (Table 3).

Table 4: Tasks performed by participants for motion capture collection.

Task #	Task Description
Task 1	Obtain their most comfortable position looking ahead and hold for approximately 10secs of motion capture.
Task 2	Stare at the center of the screen on the bottom monitor and hold for approximately 10secs of motion capture.
Task 3	Stare at the center of the screen on the top monitor and hold for approximately 10secs of motion capture.
Task 4	Find and click Report Status button in chat window.
Task 5	Find Contact 05 on the top screen. Right click on the contact and select active camera look here option from the pull-down menu.
Task 6	Take a picture of Contact 05 using joystick functions.
Task 7	Click on alert banner that appears across the top of the top screen.
Task 8	Enter the following message in the chat window. "Eagle 1 is returning to base."
Task 9	Find and Open the Emergency Procedure binder. Locate the Procedure for Engine Oil Pressure Low and read the first step.
Task 10	Reobtain their most comfortable position looking ahead and hold for approximately 10secs of motion capture.

Tasks 1 and 10 were both designed to assess the neutral position of the participants for quantifying difference between neutral for the eight experimental tasks, Tasks 2 - 9. The experimental tasks were included to represent routine tasks that were necessary during longer simulation missions. Each of the ten tasks were performed three times in chronological order for

all three collections. Upon completion of the three sets of collections on the first console, the participant was asked to perform these same tasks on the other console. Again, each task was performed and recorded three times. The order in which participants sat at each of the consoles was randomized and counterbalanced. Data collection took approximately 45 minutes. Participants received \$50 in cash payment for participating in the study.

3.2.4. Data Processing & Statistical Analysis

The independent variable for this study was the console design. The experiment was gender balanced and gender was evaluated in the initial analysis. However, gender effects were not significant and there were no interactions likely because eye height was set at 49” for all participants. As a result, gender was not included in subsequent analysis. The primary dependent variable was the mean head-tilt angle defined as the angle above horizontal of the ear-eye line (Canthus to Tragus; Figure 12). An average of this angle for each of the three observations was calculated for each task at each console. Split-plot, mixed model analysis of variance (ANOVA) models were used to compare the effects of console design for each task using IBM SPSS Statistics software Version 26 (International Business Machine Corporation, New York). The within subject factor for this experiment were the two console designs: (1) the VTUAV Ground Control Station and (2) the MD-4 Mission Control Station. Analysis was performed to determine significance ($\alpha = 0.05$) of the within-subject effect.

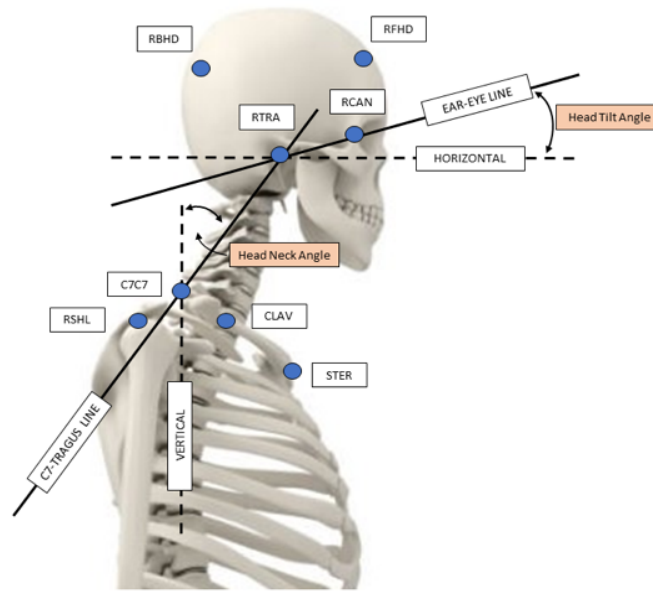


Figure 12: Head Tilt and Head-neck angles using associated MOCAP marker nomenclature.

3.3. Results

Differences in mean neutral position values measured in Task 1 and Task 10 were extremely small (approximately 0.4 degrees) indicating that participants had consistent neutral positions. Since the values for Task 1 and Task 10 were so similar, one mean neutral position value was used for each participant by calculating the mean head-tilt angle of Task 1 and Task 10. Additionally, upon further consideration, Task 9 did not involve interacting with the monitor display. This task was included to evaluate angles associated with reading from a checklist binder. However, due to the design of the consoles, there was no clear space to place reading material that did not interfere with access to the keyboard. As a result, data for Task 9 was excluded from the analysis.

The neutral head-tilt angles were virtually identical across the two consoles. The collective neutral mean head-tilt angle for the VTUAV GSC was 24.2° ($SD = 7.43^{\circ}$) while the neutral mean head-tilt angle for the MD-4 MCS was 23.9° ($SD = 7.70^{\circ}$). Data from Tasks 2 - 8

were considered individually and collectively as shown in Figure 13. The cumulative mean head-tilt angle of Tasks 2-8 were more neutral when using the MD-4 MCS console (2.02° above neutral) relative to when using the legacy console (3.79° above neutral; $F_{1,19} = 11.740$, $p = 0.003$, partial $\eta^2 = .382$). Individual Tasks 2, 3, 4 and 5 were statistically significantly different with the MD-4 MCS console providing improved head-tilt angles. The MD-4 MCS console led to lower head-tilt angles for Tasks 2 and 4 (7.48° below neutral and 7.43° below neutral) compared to the legacy console (4.13° below neutral and 5.13° below neutral; Task 2: $F_{1,19} = 16.625$, $p = 0.001$, partial $\eta^2 = .467$; Task 4: $F_{1,19} = 8.401$, $p = 0.009$, partial $\eta^2 = .307$). For Tasks 3 and 5, the MD-4 console led to more neutral head-tilt angles (8.92° and 8.30° above neutral) compared to the legacy VTUAV GCS console (12.5° and 12.3° above neutral; Task 3: $F_{1,19} = 18.943$, $p < 0.001$, partial $\eta^2 = .499$; Task 5: $F_{1,19} = 34.949$, $p < 0.001$, partial $\eta^2 = .648$).

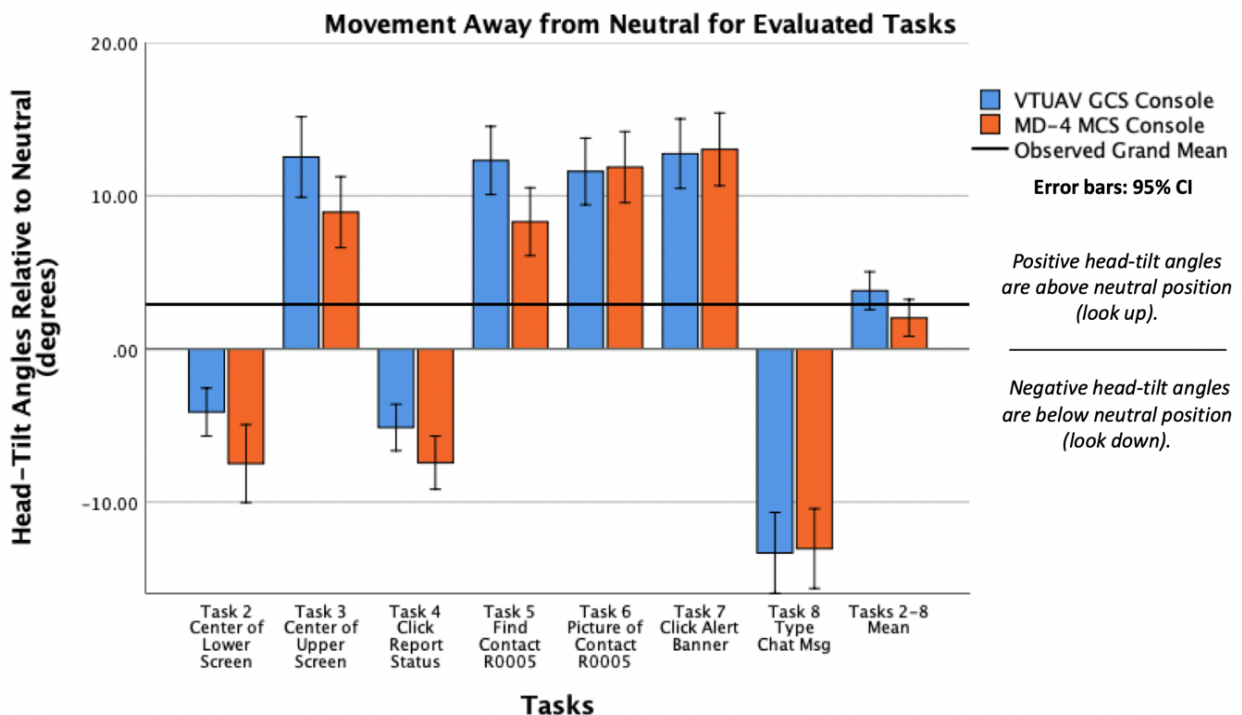


Figure 13: Head-tilt angles relative to neutral for specific tasks. Neutral shown as 0°.

3.4. Discussion

The U.S. Air Force Research Laboratory has identified MSDs as a cause for concern among UAS operators (Chappelle et al. 2012; 2017). Two studies conducted by Chappelle et al. in 2012 and 2017 found that self-reported headaches, eye strain, vision problems and musculoskeletal issues were significantly more prevalent for UAS operators than USAF personnel performing support/logistics functions. The design of UAS workstations, length of missions and pace of operations may contribute to vision problems and headaches as well as increased medical care and MSDs among UAS operators. A separate study by Ouma et al. in 2011 found that confined space and poor ergonomics of UAS ground control stations can lead to physical and psychological distress for UAS operators. It has been shown by Hill and Kroemer (1986) and Ankrum and Nemeth (2000) that the proximity of monitors and required focal length may cause humans to lower their gaze angle as monitors are positioned at closer distances. As a result, humans will adopt non-neutral (extension) head-tilt angles to allow for a more downward gaze angle. This would be even more severe for higher monitors with more extension required.

The results of the present study demonstrated that the improved design of the MD-4 MCS console reduced head-tilt extension angles in upward looking tasks and increased flexion in downward looking tasks. Both of these results brought the operators gaze angle toward a preferred lower gaze angle. While the observed angle differences in this study were not especially large, it is believed that they have the potential to contribute to less fatigue and discomfort from UAS operators (as reported by the program office with cognizance of these issues). Sommerich et al. (2001) suggested that there is likely not a singular position that optimizes both musculoskeletal and visual strain. So, it may be reasonable that minor improvements to decrease neck extension and lower gaze angles to more preferred positions

could reduce discomfort. This is particularly important for long duration missions. The length of UAS missions can exceed several hours. Numerous studies have indicated that prolonged sitting and static postures contribute to neck pain (Ariens 2001; Cagnie et al. 2007; De Loose et al. 2008). If UAS operators overexert themselves to use UAS interfaces or are uncomfortable when looking at console monitors, then their performance could degrade. Ouma et al., (2011) and Chappelle et al. (2012; 2017) arrived at similar conclusions that operational tempo, technology and GCS design may negatively impact the health of the operator. Moreover, Ouma et al. (2011) concluded that the human operator may be the most critical component to the UAS, and that military leaders should be attuned to how operator health impacts safe and effective UAS operations.

This study had several limitations. The participants did not spend a substantial amount of time in front of the consoles relative to the duration of some UAS missions. Thus, it was not possible to evaluate how continued use of the consoles may have led to differences in discomfort associated with prolonged use. The tasks used for this evaluation were representative of tasks commonly performed when monitoring multiple UAS. Using motion capture to quantify head-tilt angles over a full-length mission time period (>4hrs) was deemed impractical given the amount of storage required for even small or modest time periods of motion capture.

A subsequent study could examine longer missions to quantify the amount of time spent at each posture and the frequency of the action to provide a more holistic evaluation of the workstation design. It would be helpful to know the proportion of time spent in non-neutral postures that could lead to long-term effects. This could be also be paired with eye tracking technologies that could provide a more comprehensive analysis. Similar to studies completed by Turville et al (1998) and Sommerich et al (2001), EMG could be used to evaluate the muscle

activity associated with the tasks and consoles. This study did not consider other alternatives to the screen displays such as horizontal arrangement of the monitors. Many ergonomic desks and gaming consoles utilize multiple monitors arranged horizontally. A horizontal array of monitors may allow more comfortable head-tilt angles. Such an arrangement would introduce additional twisting and rotation which would need to be evaluated as to whether or not it contributes to neck pain in UAS operations. A search of recent studies on the association between neck pain and neck rotation caused by computer and office work found conflicting findings. Ariëns et al. (2001) conducted a prospective cohort study of over one thousand Dutch workers and found a correlation between duration of seated work posture and neck pain as well as neck flexion and neck pain. However, they did not observe an association with neck rotation and neck pain. De Loose et al. (2008) conducted a study on approximately one thousand office workers for the Belgian Defense Ministry and found that “working in a bent or twisted posture for a prolonged time was the most important physical risk factor in the military population” (De Loose et al. 2008, pg. 476). A more recent meta-analysis involving data from 12 studies representing over 18,000 participants found that excessive screen work should be limited to prevent neck pain and other associated upper extremity issues (Coenen et al. 2019). However, none of these studies provided conclusive evidence that neck rotation is associated with neck pain. They all agreed that prolonged screen use and static postures will lead to neck pain. So, regardless of the arrangement of monitors used in UAS operations, prolonged screen time will continue to be an issue that must be managed and should be explored further as it pertains to UAS operations.

3.5. Key Points

- The alternative console design provided more neutral head-tilt angles for most tasks.
- The mean neutral position for participants was 24° above horizontal.
- Additional research is needed on muscle fatigue and neck pain associated with prolonged UAS operations.

Chapter 4

Human Performance in Highly Automated, Cyber Vulnerable Unmanned Aerial Systems: Effects of Cyber Events on Performance, Workload and Trust

4.1. Introduction

Small, unmanned aircraft have become readily available to hobbyists, while corporations have considered drones for applications such as surveying remote areas for agriculture, utilities, and construction as well as commercial package delivery (Canis 2015; Stolaroff 2014). Additionally, UAS (large and small) are integral to today's military capabilities. Unmanned aircraft require a network connection to facilitate control inputs to the vehicles (direction, altitude and airspeed adjustments) and the sharing of information outside of their platforms as well as to connect the operator, supervisor, and user interfaces to a system or a series of systems (Yağdereli, Gemci, and Aktaş 2015). These types of systems are often referred to as a CPS, and they are particularly vulnerable to cyber intrusions that may result in losses of control, spoofing, degraded performance or adversarial monitoring of system parameters for intelligence purposes (Goppert et al. 2014).

The human operator is an integral part of any CPS (Thompson 2014). Automation, while intended to ease the workload of human operators and make jobs safer, may still require humans to make critical decisions. Humans must rely on timely and appropriate indicators that should inform both automated and human responses. While fully autonomous systems are developed, improved, and refined, semi-autonomous systems will require human operators or supervisors to make decisions that may affect efficiency, productivity, safety, and mission accomplishment (Endsley 2017). While other research rightly focuses on hardening, protecting and preventing CPS from cyber intrusions and vulnerabilities, adversaries will continue to find and exploit new

vulnerabilities as technology continually evolves. While intrusions can occur, research is needed to understand the impact of cyber intrusions on human and CPS performance.

The human operator primarily plays a supervisory role in highly reliable automated systems (defined as >99% reliability by Parasuraman et al., 1993). Humans, however, are notoriously poor at supervising as they become easily distracted and complacent (Parasuraman, Molloy, Robert, and Singh, Indramani 1993; Parasuraman, Mouloua, and Molloy 1996; Bailey and Scerbo 2007; Endsley and Kiris 1995; Endsley 2017). As a result, engineers often augment CPS with visual and audible warnings to alert the human of key information and degradations.

The military has invested heavily in UAS as removal of the aviator from the system eliminates physical risk to the aviator, frees up weight and space to add mission capabilities, and increases endurance. Financial commitments to research, develop and acquire autonomous and semi-autonomous systems are enormous. The Department of Defense allocated approximately \$4.5 billion each year from 2014-2016 for unmanned vehicles and associated technology (Gettinger 2017). With highly reliable, semiautonomous vehicles, single operators may, in some cases, be able to monitor multiple UAS. This allows for greater area coverage by using multiple UAS to overlay sensor footprints. This model, however, is in stark contrast to the traditional model for multi-crew manned aircraft which accounts for the preponderance of manned aircraft in the U.S. military inventory. While a single operator may be able to monitor multiple UAS that are highly reliable and highly automated, it is not likely that this model can be sustained if the reliability and automation of the UAS degrades as a result of cyber intrusion or the operator's resources become saturated. Endsley (2017) describes the "automation conundrum" where highly reliable automation is added to a system, requiring less attention devoted by the operator. As a result, situational awareness decreases and critical information may be missed if the

operator is out-of-the-loop (OTL) and the automation quality changes unexpectedly (Endsley 2017).

An operator's ability to continue to perform in a degraded system may also depend on their background experience operating similar technology. Given the costs associated with training an aviator, "gamers", defined here as individuals that play video games ≥ 10 hours per week, may be a viable alternative for UAS operators. Studies by Wheatcroft et al. (2017), Lin et al. (2015), and McKinley and McIntire (2009) previously concluded that gamers could be a viable experience group for UAS operations. Specifically, McKinley and McIntire (2009) concluded that "cognitive skills learned in video game play may transfer to novel environments such as UAS operation" while Lin et al (2015) concluded that "Gamers may have a particular aptitude" for UAS operations. This may be because gamers are able to process a significant amount of information and make decisions quickly from their live action gaming experience. Their ability to process much of this information quickly may also be attributable to their willingness to trust automation more.

Workload and task loading as a function of the level of automation were included in the study completed by Lin et al. (2015). They found that the more gaming experience a participant had, the more trust they placed in automation as workload increased. Parasuraman et al. (2009) evaluated the effects of adaptive automation on human performance in controlling unmanned ground vehicles. They found that participant performance in change detection and situational awareness improved for static and adaptive autonomy conditions when compared to manual control. They also found that adaptive autonomy was more beneficial than static autonomy. Clare et al. (2015) evaluated participant gaming experience (gamers vs. non-gamers) and three levels of trust priming (positive priming, no priming and negative priming) to determine if

priming gamers with trust information altered their performance in a collaborative scheduling interface and controlling multiple unmanned vehicles. Results suggested that negatively priming gamers to lower their initial trust of an automated system increased their performance within the system. These studies, however, did not consider cyber threats.

Satterfield et al (2018) conducted one of the few studies evaluating human performance in recognizing cyber events in UAS platforms. Specifically, their cyber events resulted in the UAVs stopping on their assigned flight path. These attacks were presented both in and out of the gaze view of the participant. Their results indicated that approximately 64% of the participants noticed the attack, but they required several questions that prompted them to recall what may have been evidence of a cyber event. It is not clear if the participants were warned ahead of time as part of an orientation to study participation as to the type of cyber event that was possible or instructed on how it may manifest itself. It also unknown what background the participants in this study had or their experience in aviation scenarios.

Despite the strengths of these studies, additional research is needed to examine the effects of operator background and task loading while controlling multiple UAS in a cyber-compromised environment. The objective of this study was to evaluate the effects of operator background (aviator, gamer and non-gamer) and task loading (in-the-loop [ITL] and OTL) on operator ability to detect and respond to cyber events while controlling multiple UAS. It was hypothesized that gamers would respond as quickly and accurately to cyber events as aviators, while non-gamer control participants would respond more slowly and less accurately than both groups. It was assumed that performance would improve across all groups for the OTL condition compared to the ITL condition.

4.2. Methods

4.2.1. Participants

Study participants were 51 students recruited from the Auburn University community. All participants were US citizens, 19-42 years old, and had 20/20 corrected vision. Participants were divided into three balanced background groups: Aviators, Gamers and Non-Gamers. Aviators were defined as those with civilian flight time of at least 40hrs (Federal Aviation Authority minimum flight time requirement for a civilian single engine pilot license). Gamers were defined as those participants who did not meet the aviation threshold and played video games ≥ 10 hrs per week. Non-Gamers were defined as those who did not meet the aviation threshold and self-reported playing video games < 6 hrs per week. The gaming experience threshold of six and ten hours were strategically selected. Winn and Heeter (2009) studied 276 undergraduate students from a single American university and determined that the average male college student plays approximately 5.3 hours of video games a week. In contrast, the Entertainment Software Association estimated in 2015 that frequent gamers play approximately 11.5 hours of games per week with other gamers. Participants were compensated \$50 for completing the study. All participation was completed in one time period that began with documented informed consent in accordance with the Auburn University Institutional Review Board (IRB).

For this study, the aviators self-reported an average of 215.8 hours of civilian flight time per FAA log and 1.1 hours of gaming per week. None of the aviators reported more than 6 hours of gaming per week. The gamers averaged 19 hours of gaming per week (self-reported). All non-gamers self-reported zero hours of gaming per week.

4.2.2. Overview of Experiment

Participants operated a generalized, single-operator, multi-UAS simulation created by personnel in the NAVAIR Human Systems Department (4.6) across three scenarios: an introductory training scenario and two, one-hour long experimental scenarios. The experimental scenarios included one ITL and one OTL scenario. The ITL scenario required directing up to four UAS (Eagle-1, Eagle-2, Eagle-3 and Eagle-4) by controlling airspeed, heading and altitude. The four UAS flew a preassigned flight path profile via autopilot so that the participants were not responsible for their airspeed, heading and altitude in the OTL scenario. All participants completed one ITL and one OTL scenario after completing the training scenario. The order of OTL and ITL scenario was randomly assigned and counter-balanced across participants.

4.2.3. UAS Interface and Control Station Design

The UAS user interface and simulation environment represented a generalized UAS control environment with many of the same features found on actual UAS control station displays. However, the simulation environment used open source, unclassified and, in some cases, artificial performance parameters for surface and air contacts as well as radar and payload camera capabilities. The control station included a joystick, keyboard, mouse, and two 24" monitors (Figure 14). The physical dimensions of the control station used for this study, monitor heights, screen size, angles of the screen, position of the keyboard and joystick were identical to a UAS control station currently in use by the U.S. Navy. The UAS control station interface included functions to manage platform and mission information, navigation control, payload control of a Forward-Looking Infrared camera on all assets, and map and radar information. Vehicle and payload models were created at NAVAIR's Human Computer Interaction Lab.

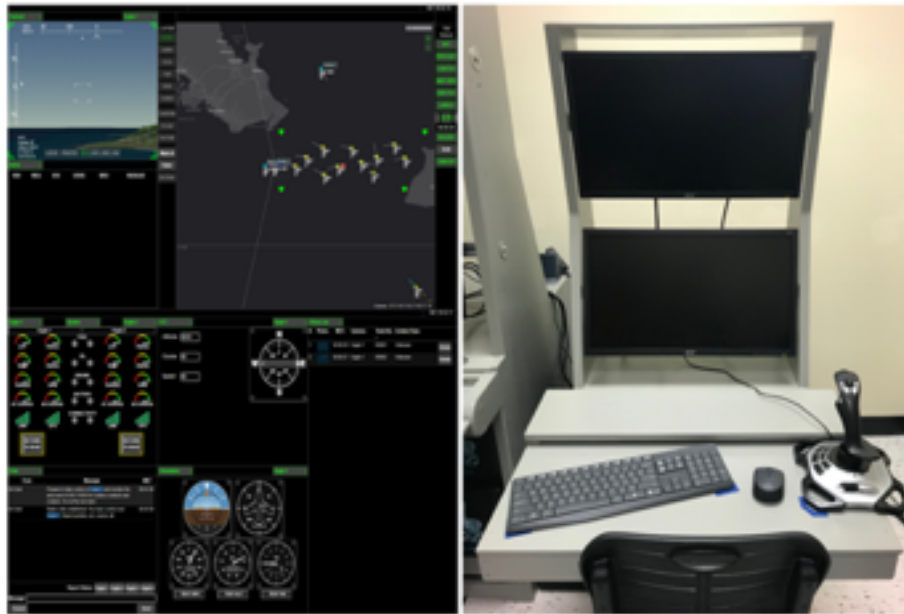


Figure 14: User interface and UAS control station mockup.

The top screen housed three display areas that included (from top left and moving clockwise): Payload Display (or camera view), Map Display, and Alert Information Display. A visual banner was illuminated across the top of the top screen to alert the user of a system degradation when an alert was active. Participants were instructed that clicking on the banner would suppress its appearance allowing for a subsequent alert banner to appear when another alert was warranted. If not clicked, all subsequent alerts would be masked behind the initial alert until clicked to clear. Once clicked to clear, participants were instructed to scan down to the alert panel for additional information and then on to the bottom screen to check system instruments to corroborate the alert.

The bottom screen housed five display areas including (from top left and moving clockwise): a System Status display, Flight Control Display, Photo Library Display, Orientation Display, and Chat Window. The System Status Display housed digital gauges for up to two UAS

at a time. Participants could select which vehicles they were interested in viewing the gauges for via a dropdown menu. The gauges included a variety of vehicle systems such as Fuel Quantity, Fuel Pressure, Oil Temperature, Oil Pressure, Battery Charge, Link and GPS Status. The System Status Display also had digital buttons that allowed the participant to send the vehicle back to base. Clicking the “Return to Base” button put the vehicle on an automated return to base profile that required no additional input from the participant.

The Flight Control Display was where participants could enter and control airspeed, heading and/or altitude for a single UAS. This was functional in the ITL scenario only and not enabled for the OTL scenario since each UAS was on a predetermined flight path. The Flight Control Display allowed input to one vehicle at a time. Inputs to multiple vehicles had to be completed individually by selecting the appropriate vehicle via a dropdown menu. The Photo Library Display showed all pictures taken with the onboard cameras from all four UAS. As contacts were classified, the library displayed the classification associated with each picture. The Orientation Display showed five digital gauges familiar to those with an aviation background. These were an attitude gyro, heading indicator, speed indicator, radar altimeter, and vertical speed indicator. These gauges were not required to operate the vehicle since the information existed in other panels but were included for consistency with current practices. The Orientation Display allowed participants to monitor a second vehicle’s parameters via gauges in addition to those parameters shown in the Flight Control Display. Finally, the chat window was a running dialogue with the participant and the simulated mission controller. The interface provided pre-scripted chat messages from the mission controller that participants read. Responses from the participants were shown in the chat window.

4.2.4. Experimental Task

For both experimental scenarios, the participants' primary mission was to detect and classify up to twenty-one unknown surface contacts. Participants were instructed to take a picture with the payload camera and classify the contact as a merchant vessel, fishing trawler, sailboat or other using a dropdown menu. One of the 21 contacts was a vessel in distress (a fishing vessel on fire). In addition to classifying all surface contacts, participants were instructed to locate, report the position, and to digitally mark the vessel in distress by selecting a point-of-interest marker from a dropdown menu in the user interface. Participants were instructed to read all chat messages and respond to those that required a response. There were ten chat messages that required a response and were subsequently evaluated for response and response time.

Participants were presented with twelve “real” events and three “cyber” events throughout each experimental scenario. Real events were defined as alerts that could be corroborated with secondary instruments. For example, a real fuel emergency could be indicated by an independent fuel low light and corroborated by a corresponding fuel level gauge. Conversely, cyber events were those that could not be corroborated, simulating that an adversary may have modified information. Therefore, continuing with the fuel emergency example, a fuel low light could indicate a cyber fuel emergency, but the corresponding fuel gauge shows sufficient fuel. The cyber events created and presented in the simulation environment were based on exploitation of vulnerabilities identified by Yağdereli, Gemci, and Aktaş (2015). Participants were tasked with correctly classifying each event as either a real or cyber event as well as take an appropriate action (continue flight or return to base) using the procedures and checklist provided in the emergency procedures binder. Participants were instructed to report all events, real and cyber, via chat using the following format:

*“Eagle-# (1,2,3, or 4), System Affected (Oil Temp, Fuel Pressure, etc),
Classification (Real or Cyber), Action (Continue or Return to Base).”*

4.2.5. Instruction and Training Scenario

Prior to data collection, all participants completed an initial training scenario that included approximately thirty minutes of instruction, followed by a twenty-minute training simulation. All instruction provided to the participants was conducted by the lead researcher using the same script and information for every participant. Instruction consisted of explanation on the contact classification mission, including types of contacts, as well as an explanation and demonstration of the user interface functions. Participants were also provided with a simulation procedure binder that contained procedures for each system alert that may be presented during the simulations. These procedures were applicable to real and cyber events.

For the training scenario, participants controlled two independent UAS and were presented with a smaller search area containing ten unknown surface contacts, a variety of chat messages to read and respond to, and two real system degradations with corresponding alerts. Satisfactory completion of the training scenario was defined as successful classification of six (of ten) surface contacts and a correct response to one (of two) real events. All 51 participants met these minimum performance standards. Any participant questions were answered by the lead researcher during the thirty-minute instructional period. Additionally, participants were encouraged to ask any questions during the twenty-minute training scenario. Furthermore, participants were told that questions during both experimental scenarios would not be answered.

4.2.6. Task Load and Trust

The NASA TLX (Hart and Staveland 1988) was used to assess operator workload. The NASA TLX was delivered in three stages. Immediately following completion of the training scenario, but before completing an experimental scenario, participants made 15 pairwise comparisons to establish the weight of the six factors/scales used in the TLX. Participants then provided responses to the six factors of the TLX following each experimental scenario. Measurements of each survey scale response were made to the nearest 1/16 of an inch and then normalized as a percentage of the line length. Other studies have used the scale similarly (Hart 2006). All measurements of the survey scale responses were performed by one researcher and verified by the lead researcher. The mean weighted score for each participant was calculated by multiplying the personalized weights (0 for irrelevant to 5 for most important) for the six scale categories, as gleaned from the pairwise comparisons for each participant, by the normalized score as measured by the researchers. The weighted scores for each scale category were then summed to give an overall mean weighted average (MWA) workload score for each participant.

The Trust between People and Automation Survey (Jian et al., 2000) was used to assess operator trust in the system. Responses were collected following the completion of each task load scenario by having participants mark their responses on separate survey response sheets for each of the 12-items included on the scale (Likert 1-7). Similar to the TLX data, these responses were quantified by a single researcher and verified by the lead researcher.

4.2.7. Analysis

Split-plot, mixed model analysis of variance (ANOVA) were used to analyze each dependent performance, workload and trust variable (Table 1) for the three background groups

across both task load conditions using IBM SPSS Statistics software Version 26 (International Business Machine Corporation, New York). The between subject factor was participant background: Aviator, Gamer, or Non-Gamer (control). The within subject factor for this experiment was the task load type: ITL and OTL. Tukey pairwise comparisons were performed and analyzed to determine significance ($p < 0.05$) of the three background groups. Kaplan-Meier survival analysis was used to evaluate the time to first missed chat message for all background groups and both task loads.

Table 5: Summary of independent and dependent variables analyzed in this study.

Independent Variables	Categories
Background	Aviator, Gamer, or Non-gamer
Task Load	In-the-Loop (ITL) or Out-of-the-Loop (OTL)
Dependent Variables	Units
Contacts Classified Accuracy	Percentage (%)
Chat Message Response Accuracy	Percentage (%)
Chat Message Response Time	Seconds (secs)
Real Event Classification Accuracy	Percentage (%)
Real Event Action Accuracy	Percentage (%)
Real Event Response Time	Seconds (secs)
Cyber Event Classification Accuracy	Percentage (%)
Cyber Event Action Accuracy	Percentage (%)
Cyber Event Response Time	Seconds (secs)
NASA TLX Mean Weighted Average	Continuous Scale (0-100 value)
Trust Value	Likert Scale (1-7 whole number value)

4.3. Results

4.3.1. Contact Classification Performance

The mean accuracy of contact classification exceeded 97% for all background groups indicating excellent performance for the primary task. A statistically significant interaction between task load and background ($F_{2,48} = 3.33, p = 0.04$, partial $\eta^2 = 0.12$) was observed where non-gamers' contact classification accuracy was lower than that of aviators and gamers in the OTL task load. Aviators' and gamers' mean contact classification accuracy increased from 98.3% and 98.9% for the ITL task load to 99.4% and 99.2%, respectively, for the OTL task load. Conversely, the non-gamers' mean contact classification accuracy decreased from 98.0% for the ITL task load to 97.2% for the OTL task load.

4.3.2. Chat Message Performance

No statistically significant differences in chat message accuracy or response time were observed among the three groups. Kaplan-Meier survival analysis indicated a statistically significant effect of background on time to first failure for the OTL task load ($p = 0.01$) where aviators and gamers performed substantially better than non-gamers (Figure 15). Censored survival percentages for aviators, gamers and non-gamers were 52.9%, 47.1%, and 11.8%, respectively for the OTL task load.

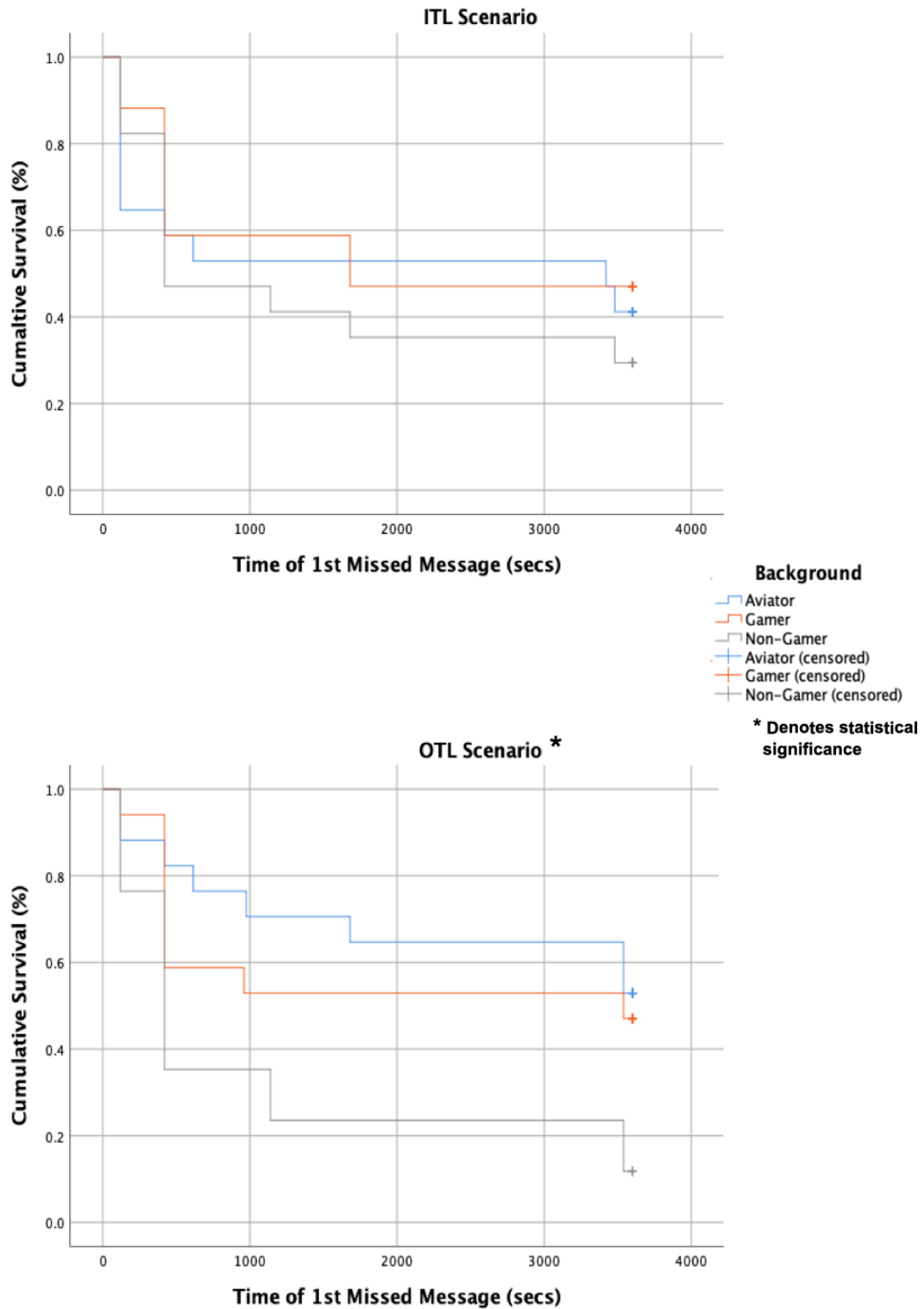


Figure 15: Kaplan-Meier Survival plots for First Missed Chat Message.

4.3.3. Real and Cyber Event Performance

Real and cyber events were analyzed using three metrics, classification accuracy, action accuracy and response time. Statistically significant main effects of task loading ($F_{1,48} = 37.47$, $p < 0.001$, partial $\eta^2 = 0.44$) and operator background ($F_{2,48} = 4.42$, $p = 0.017$, partial $\eta^2 = 0.16$) were observed for cyber event classification. Task loading resulted in collective error rates of 29.2% for the ITL task load condition compared to 19.5% for the OTL task load condition. Non-gamers classified cyber events at a statistically significantly worse percentage than gamers ($p = 0.02$), but not aviators ($p = 0.09$; Figure 16). Non-gamer cyber event classification error percentages for the ITL and OTL task load conditions were 39.1% and 19.5%, respectively, compared to gamer's cyber event classification error percentages of 16.7% and 7.8%. A statistically significant main effect of task loading ($F_{1,48} = 26.04$, $p < 0.001$, partial $\eta^2 = 0.35$) was also observed for cyber event action accuracy with collective error rates of 25.5% for the ITL task load condition and 1.00% for the OTL task load condition.

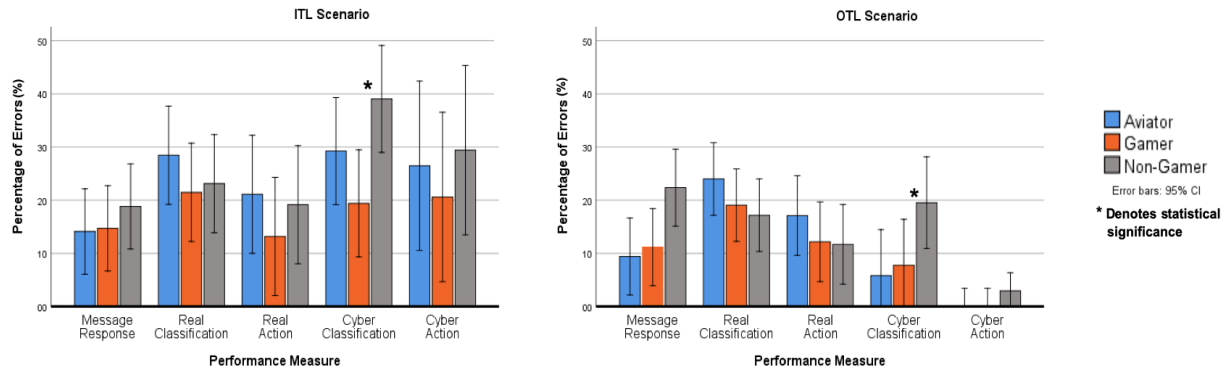


Figure 16: Error rates for chat messages, real events and cyber events by task loading condition for all background groups. Statistically significant main effects of task loading ($F_{1,48} = 37.47$, $p < 0.001$, partial $\eta^2 = 0.44$) and operator background ($F_{2,48} = 4.42$, $p = 0.017$, partial $\eta^2 = 0.16$) observed for cyber event classification. Statistically significant main effect of task loading ($F_{1,48} = 26.04$, $p < 0.001$, partial $\eta^2 = 0.35$) observed for cyber event action accuracy.

A statistically significant main effect of operator background was observed for cyber event response times $[(F_{1,48}) = 3.63, p = 0.03, \text{partial } \eta^2 = 0.13]$, where non-gamers mean response time across both task load conditions was 191.8 secs compared to 100.1 secs for aviators and 94.84 seconds for gamers as shown in Figure 17. Response times for cyber events were appreciably greater than those for chat messages and real events. Mean response times across task loading conditions for cyber events was 128.9 secs compared to 42.8 secs for non-cyber, “real” events. Task loading did not significantly affect response time to real events and/or cyber events.

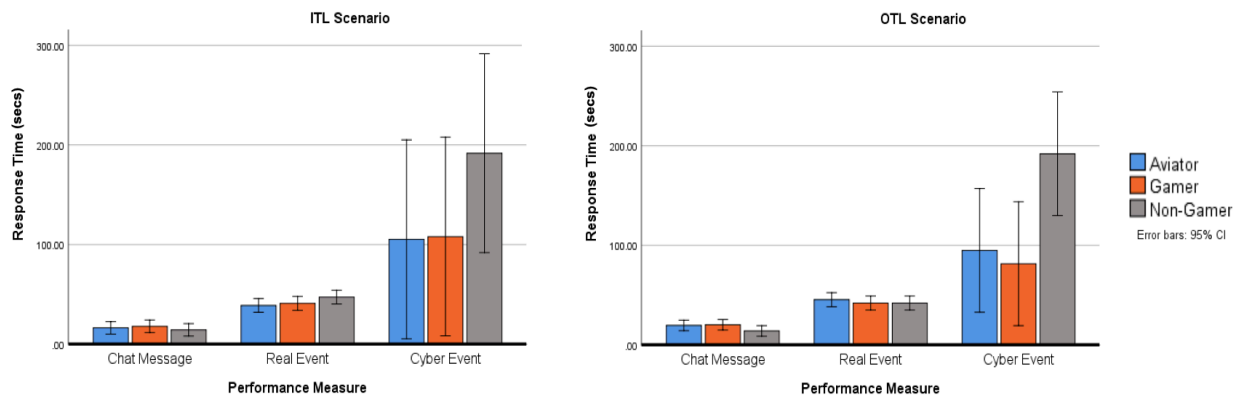


Figure 17: Response times for chat messages, real events and cyber events by task loading condition for all background groups. Statistically significant main effect of operator background observed for cyber event response times $[(F_{1,48}) = 3.63, p = 0.03, \text{partial } \eta^2 = 0.13]$. Aviators and gamers approached statistical significance at $p = 0.071$ and $p = 0.053$, respectively.

4.3.4. Workload

Workload, as measured using the NASA TLX, was affected by task loading ($F_{1,48} = 9.34, p = 0.004, \text{partial } \eta^2 = 0.163$) with the MWA for the ITL condition at 36.14 and the MWA for the OTL condition at 28.66. Four of the six workload factors were statistically significant and affected by task loading. These were Mental Demand $[(F_{1,48}) = 13.89, p < 0.001, \text{partial } \eta^2 = 0.22]$, Physical Demand $[(F_{1,48}) = 5.31, p = 0.026, \text{partial } \eta^2 = 0.10]$, Temporal Demand $[(F_{1,48}) =$

4.64, $p = 0.036$, partial $\eta^2 = 0.09$], and Effort [$(F_{1,48}) = 0.84$, $p = 0.012$, partial $\eta^2 = 0.13$].

Background did not have a significant effect on the six workload factors. However, it may be worth noting that Mental Demand ($p = 0.08$) and Own Performance ($p = 0.09$) demonstrated trends towards significance.

4.3.5. Trust

Trust values were not statistically significant for the three background groups or the two task load conditions. However, trust values were statistically significant when comparing the change in trust from the conclusion of the first task load scenario (ITL or OTL) and the conclusion of the second task load scenario (ITL or OTL), with scores increasing slightly across all groups ($F_{2,48} = 5.30$, $p = 0.03$, partial $\eta^2 = 0.10$). Collective participant mean trust values increased from 3.31 after the first scenario to 3.42 after the second scenario.

4.4. Discussion

Many studies have examined human performance in automated systems (Endsley 2017). Gaming experience and levels of automation in UAS operations have been evaluated in several previous studies (Clare, Cummings, and Repenning 2015; Wheatcroft et al. 2017; Lin et al. 2015; McKinley et al. 2009; Parasuraman, Cosenzo, and De Visser 2009; Satterfield et al. 2018). Similar to the results of Wheatcroft et al. (2017), Lin et al. (2015) and McKinley et al. (2009), the findings of the present study suggest that civilian gamers may perform as well as civilian aviators when controlling multiple UAS and being faced with context-relevant real and cyber events despite having no manned flight experience. As hypothesized, gamers committed less errors and responded at least as quickly as aviators for the performance metrics of chat message,

real events, and cyber events responses. Perhaps this is not surprising given the video game-like design of the user interface. With many UAS system user interfaces, “stick and rudder” skills may not be necessary. The systems are highly automated and inputs to altitude, heading and airspeed are often made via keyboard strokes and mouse clicks as opposed to conventional manned flight control inputs. Joystick control is often only needed for controlling payload cameras. Overall, this is an important finding as some military services require designated aviators who are trained in manned aircraft flight school to operate UAS.

Cyber events contributed significantly to response time for all groups when compared to routine chat message and real event response times. Cyber event response times for aviators (100.08 secs) and gamers (94.80 secs) were more than twice as long when compared to their real event response times, 42.16 secs and 41.49 secs, respectively. Even worse, non-gamer cyber event response time (191.84 secs) was more than four times greater when compared to their real event response time of 44.64 secs. This finding suggests that cyber events will take longer to diagnose and to appropriately respond. In time critical tasks, this could mean the difference in mission success and failure or even the survival of the UAS platform. These failures would most certainly have trickle down effects on those reliant on the information and capabilities the UAS provides. Similarly, an overwhelming number of cyber events may be enough to saturate the operator due to the significant amount of time required to respond when compared to more routine or real events. This impact would be compounded further if a single operator was monitoring or controlling multiple UAS that experience cyber events.

Not unexpectedly, task load was often a performance driver in this study. The OTL task load afforded more time for the operators to perform their tasks, likely leading to the observed performance improvements when compared to the ITL condition. One noted exception was non-

gamer performance. While aviator and gamer contact classification accuracy increased from the ITL to the OTL task load, non-gamer accuracy decreased. It is believed that this finding is likely attributable to one contact that could only be identified toward the end of the OTL task load condition. If errors were made in event classification and action resulting in returning a vehicle to base that should have remained in flight, a participant would not be able to classify this final contact. More non-gamers sent a UAS back to base inappropriately during the OTL task load leading to a decrease in the percentage of contacts that could be identified. This is significant in that this response resulted in what the military calls a “mission kill” where the UAS is no longer available to perform its mission due to human error by the non-gamer operator.

It is important to note that non-gamer and gamer participants had no reported civilian flight time, while each aviator participant had an average of 215.8 flight hours. Per the FAA, forty hours is the minimum number of hours needed to obtain a private pilot license. The average flight time of a designated naval aviator coming out of flight school is approximately 200hrs. While the types of flight events certainly vary between military and civilian training, the hourly experience is comparable for the aviation participants of this study and the flight hour experience of the newest naval aviators. This is an important strength of the study.

It is also worth revisiting the gaming experience of the participants. Gamer and non-gamer participants had no flight experience; however, gaming hours among aviators was not controlled. Ideally, aviators and non-gamers would have zero gaming experience. The non-gamers who performed worse than the other two background groups had no self-reported gaming experience. Gamers self-reported playing approximately 19hrs of video games per week while aviators reported approximately 1hrs of gaming per week. It was not evaluated, nor is it apparent, what level of gaming experience is sufficient to perform similarly to the aviation participants in

this study. This could be examined through a future study with participants whose gaming hours are systematically controlled.

The nature of cyber threats presents a unique challenge when conducting academic research due to the inherent security classification of such threats. The threats presented in this research were identified in open-source academic publications as known threats to UAS. Additionally, a notional, generalized and unclassified UAS control user interface was used. As a result, the presentation had some artificial aspects for the cyber threat presentation. More applied research would benefit from conducting a similar study at the appropriate classification level using platform specific simulators, certified UAS operators, and known cyber threats and vulnerabilities. Finally, this study would have been stronger if military UAS operators were a fourth background group. However, this was not feasible due to logistical reasons. Despite these limitations, this research provides novel findings in the growing domain of CPS.

4.5. Key Points

- Non-gamers were significantly worse than aviators and gamers in classifying cyber events.
- Task loading was an important factor for classifying cyber events and selecting appropriate actions.
- Aviator and gamer performance were generally comparable for most metrics.
- Response time to cyber events was significantly greater than for real events.

Chapter 5

Manned Flight Training Requirements for Navy UAS Group 4 and Group 5 Operators - Costs, Benefits and Discussion on Alternative Recruiting Targets for UAS Operators

5.1. Introduction

In 2015, then Secretary of the U.S. Navy Ray Mabus stated that the F-35 Lightning will likely be the last new manned strike fighter aircraft purchased for the Department of Defense (GAO 2018). Unmanned Aerial Systems (UAS), on the other hand, comprise a substantial component of the current and future U.S. military inventory. The fiscal year 2018 (FY18) Defense budget included almost \$10 billion in unmanned systems for the U.S. Department of the Navy, including air, surface and underwater systems (GAO 2018). The 2018 U.S. Government Accountability Office (GAO) report entitled “*Military Personnel – Actions Needed to Better Position the Navy and the Marine Corps to Support Expanding Unmanned Systems Operations*” indicated that the Navy is likely to have difficulty meeting UAS personnel requirements in the future as a consequence of the growth in UAS operations and retention shortfalls in Navy manned flight communities that rely on manned flight-trained naval aviators to operate UAS (GAO 2018). The anticipated shortfall is based off of budgetary proposals for aviation retention bonuses needed to retain pilots in the Navy’s maritime patrol aircraft and helicopter communities. This shortfall is also expected in the U.S. Navy Reserve where not only do personnel dual-purpose as pilots for Navy manned aircraft and UAS, but they also have, or desire jobs, in commercial aviation.

The Navy currently requires manned flight-trained naval aviators to operate all Group 4 and Group 5 UAS, while the U.S. Air Force and U.S. Army do not require manned flight training for similar UAS platforms (GAO 2018). As the balance of manned and unmanned aircraft shifts

in the Department of Defense's inventory towards unmanned platforms, targeting recruits with specific backgrounds and implementing alternative training pipelines may provide UAS operators more quickly and at a lower cost. This paper examines the costs and benefits associated with the Navy's current approach to developing UAS operators as well as alternative personnel strategies to meet future UAS manpower needs.

5.2. Background

5.2.1. Types of UAS

UAS systems used by the military are generally separated by size with the smallest UAS categorized into Group 1 and the largest UAS into Group 5. The size of the UAS affects range and altitude of the vehicles with larger vehicles generally able to fly higher and farther. A summary of DoD UAS inventory is provided in Figure 18.

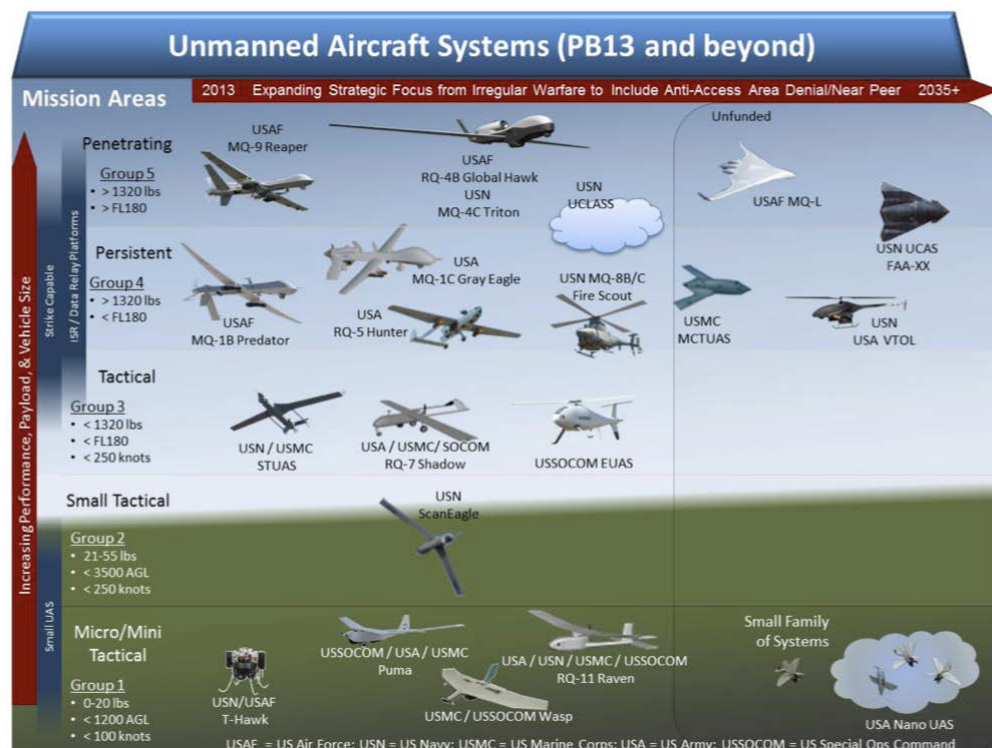


Figure 18: Summary of UAS capabilities as found in the DoD UAS Roadmap FY13-FY38 (<https://dod.defense.gov/Portals/1/Documents/pubs/DOD-USRM-2013.pdf>)

5.2.2. Policies

The Air Force currently sources its Group 4 and Group 5 UAS operators from the Air Force pilot community or from a specialized Remotely Piloted Aircraft (RPA) training program. In doing so, the Air Force has created specialized career fields and paths for RPA pilots (DoD 2013). Similarly, the U.S. Marine Corps has created a Military Occupation Specialty (MOS) for UAS operations (GAO 2018). However, the MOS is currently being used for only Group 1-3 UAS since the Marine Corps does not currently have Group 4 or 5 UAS in their inventory. The U.S. Army trains its UAS operators for Group 3 and above UAS through a dedicated UAS flight training syllabus resulting in a designated MOS (DoD 2013). They do not pull from the Army pilot community to fill their UAS operator positions.

The Navy currently requires manned, flight-trained naval aviators, otherwise known as pilots or Air Vehicle Operators (AVO) to operate all Group 4 and Group 5 UAS. According to a U.S. Government Accountability Office (GAO) report from February 2018 entitled *Military Personnel – Actions Needed to Better Position the Navy and the Marine Corps to Support Expanding Unmanned Systems Operations*:

“Only officers who are qualified as manned aircraft pilots serve as Navy air vehicle operators of UAS in groups 4 and 5, although enlisted personnel serve as payload operators or as air vehicle operators of smaller UAS. The other Services’ approaches for using military personnel as UAS operators differ. The Air Force and the Marine Corps permit both officers and enlisted personnel to serve as

UAS air vehicle and mission payload operators. Army UAS air vehicle and mission payload operators are a mix of warrant officers and enlisted personnel.” (GAO 2018, pg 26)

5.2.3. Training

In light of the current Navy policy for Group 4 and Group 5 UAS operators, it is important to consider what that training entails and the associated costs. Prior to starting flight school in the Navy, an aviation candidate must have some civilian flight training experience. This could be completed independently or through what is called the Navy’s Introductory Flight Screening (IFS) program meant to identify those who are suitable for manned flight aviation training. The IFS program takes approximately ten weeks to complete. Students then complete a classroom only phase lasting approximately six weeks called Aviation Preflight Indoctrination (API). This stage of training focuses on weather, navigation, aircraft systems, aerodynamics, and survival. Upon successful completion of API, prospective naval aviators begin actual flight instruction, called Primary, that includes simulator and flight events utilizing single engine fixed wing aircraft. Primary training is programmed as an approximately twenty-seven week curriculum, but due to weather and scheduling delays, often takes longer. Phases of this training include basic visual and instrument flight, formation flying and aerobatics. At the conclusion of Primary, students are selected for different types of aircraft that may include: Jets, Props, Helicopters, etc. They then begin their intermediate and advanced flight training that include more specific, tailored training in the type of aircraft that they will specialize in going forward. For rotary aircraft, the advanced flight training curriculum is programmed for approximately twenty-eight weeks (Figure 19). However, the duration of the training is subject to weather and

scheduling delays. The time to complete the training from IFS to designation as a pilot is estimated to take approximately two years as of FY20. More information comparing manned and unmanned operator qualifications has been summarized by Pagan et al (2014).



Figure 19: Description of the Naval Aviation Training pipeline.
(<https://www.cnatra.navy.mil/training.asp>)

Upon completion of the training, new naval aviators are assigned to a fleet aircraft and then proceed to be trained in the specific flight aircraft in a Fleet Replacement Squadron (FRS). Training time for this phase is dependent on the aircraft type but is approximately 44 weeks for rotary aircraft. Upon completion of FRS training and a brief survival school, new pilots join their first Fleet squadron.

5.3. Cost Analysis

The Navy does not require manned flight-trained operators for the Group 3 UAS such as the RQ-7 Shadow. Related research documented in 2012 reported that training for RQ-7 Shadow operators lasted 10 weeks at a cost of approximately \$350k (Pagan, Astwood, and Phillips 2014). Group 4 and 5 UAS operators, however, must come from Navy pilot officer personnel. Operators of the MQ-4 Triton aircraft (Group 5 UAS) are pilots that have completed at least one tour flying

either a P-3 or P-8 manned aircraft. For the MQ-8 Fire Scout (Group 4 UAS), operators are dual purposed as pilots of Navy MH-60 aircraft. MQ-8 Fire Scout are integrated with various MH-60 squadrons and can deploy with a mix of MH-60 and MQ-8 aircraft requiring operators who can fly both the manned and unmanned aircraft. The UAS operators for both the MQ-4 and MQ-8 receive additional training on these platforms having previously completed all manned pilot training requirements for the Navy. The training for MQ-4 and MQ-8 operators takes approximately 3 months and 2 months, respectively. The actual manned flight training time to train for MQ-4 and MQ-8 pilots, prior to any UAS training, is approximately 2.7 years and 3.1 years, respectively, as of April 2019. Therefore, the total time to train a Navy Group 4 or Group 5 UAS operator can be estimated to be approximately 3 years.

The costs associated with Navy manned flight training differ by manned aircraft type and include flight hour costs as well as support costs for classroom instruction and simulator events, among other things. Various estimates have placed the cost to train a naval aviator from the first flight school event to fleet aircraft at approximately \$1 million per pilot (Pagan et al 2014). This estimate likely includes costs for jet training; however, the Navy jet community does not currently have a UAS that it supported by dual-purposed jet pilots. Navy helicopter and maritime aircraft training estimates for FY19 indicated that helicopter training through the completion of flight school was projected to cost approximately \$353,000 while maritime aircraft training through the completion of flight school was projected to cost approximately \$310,000. These costs include approximately 190 manned flight hours for helicopter training students and 149.2 manned training flight hours for maritime aircraft training students.

For perspective, the Air Force estimated in 2014 that the cost to complete undergraduate pilot training (UPT) for a single fighter pilot was just under \$1.5M and the cost to complete UPT for one logistic mobility pilot was approximately \$750K (Norton 2016). The Air Force estimated the cost in 2014 to complete the undergraduate remote pilot aircraft training (URT) requirement for their UAS only training model was approximately \$70K (Norton 2016). Therefore, there are significant cost differences in UAS only training compared to manned flight training for the Air Force. The Army UAS training model uses two phases totaling approximately 22-35 weeks depending on the specific UAS platform type (DoD 2013) and uses only enlisted soldiers for their UAS operators. Per Army sources using FY20 dollars, the cost to train a Group 3 Army UAS operator (RQ-7 Shadow) is expected to be approximately \$100K and the cost to train a Group 4 Army UAS Operator (MQ-1 Gray Eagle) approximately \$211K.

According to Navy personnel responsible for training Fire Scout operators, the training syllabus for the MQ-8 Fire Scout takes approximately eight weeks to complete at an estimated cost of \$67K per operator. Since the Navy requires Fire Scout operators to also be manned flight-trained, the total cost to produce a Fire Scout operator should not only include the costs of Fire Scout Training (\$67K), but also MH-60 helicopter training (~\$844K for MH-60S training) and Navy Flight School training (~\$353K). Therefore, the total training cost to develop a single Fire Scout operator can be estimated to be approximately \$1.264M.

At an estimated cost of \$1.246M, the Navy's model to train Group 4 and Group 5 UAS operators dwarfs its model for Group 3 RQ-7 Shadow operators at approximately \$350k (Pagan, Astwood, and Phillips 2014). The \$1.246M price tag for the Navy Group 4 UAS (MQ-8 Fire Scout) operator training is also substantially more than similar training for Army Group 4 UAS

(MQ-1 Gray Eagle) operator training estimated to be approximately \$211K. So, the Air Force and Army train their UAS operators without manned flight training resulting in less time to train and lower costs. Perhaps there are other ways of developing UAS operators for the Navy that not only capitalizes on the models used by the Army and Air Force, but also finds candidates who are ideal for UAS operations. Thus, a review of relevant research that has been completed on UAS operator traits, skills, attributes and necessary experience is prudent.

5.4. Relevant Studies

The first deployment of the Pioneer unmanned aerial vehicle (UAV) by the Navy occurred in 1986 (O'Rourke 2006). The Pioneer was small, with a wingspan of seventeen feet, and required a crew of three personnel to operate (U.S. Navy 2013). The crew positions were comprised of two personnel responsible for flying the vehicle (Internal and External Pilots) and a Mission Commander who oversaw the conduct of the mission. Ironically, the Internal and External Pilots were not manned flight-trained pilots, while the Mission Commander, who did not fly the vehicle, was usually someone with flight experience. Training for the Internal and External Pilots took approximately 18-22wks (Biggerstaff et al. 1998).

In 1998, after several years of operating the Pioneer UAV, the Department of the Navy supported a study to identify criteria to aid pilot selection. This study was conducted after several accidents were attributed to human error. The study used a two-hour battery of cognitive and multitask tests that were used to predict how individuals might perform during training. The researchers described the test battery as “similar to a video game” and the results of the study indicated that the cognitive test battery strongly correlated to UAS training performance (Biggerstaff et al. 1998). This begs the question, if video games may be used to evaluate

potential UAS operators, should the extent to which one plays video games be considered as a positive attribute for UAS operations?

The thought that “gamers” may make good UAS operators is not new. The idea has been explored previously by the Air Force and others. McKinley et al (2009) conducted a study in support of the Air Force entitled “Operator Selection for Unmanned Aerial Vehicle Operators: A Comparison of Video Game Players and Manned Aircraft Pilots.” This study was born out of the need for more UAS operators to meet rapidly expanding number of UAS missions. McKinley et al (2009) compared the performance of video game players and pilots completing cognitive tasks used in related studies such as the Cambridge Neuropsychological Assessment Battery (CONTAB) and Multi-Attribute Task Battery (MAT-B). The cognitive skills they evaluated included, but were not limited to, situational awareness, timing, motor control and coordination, memory, multitasking and spatial awareness (McKinley et al. 2009). Pilots performed appreciably better than gamers on multitasking cognitive tests, while gamers performed better than pilots on tasks related to finding and tracking targets. Perhaps surprisingly, pilots and gamers did not perform statistically significantly different for UAS landing tasks. McKinley et al. (2009) concluded that gaming experience may be a desirable skill for UAS operators and that training operators with gaming experience may help reduce training time based on their findings.

In his thesis completed at the U.S. Air Force Institute of Technology, Triplett (2008) analyzed the skills intrinsic to video game play to those required for Predator unmanned aircraft operations. A list of overlapping skills was developed, and gamers were argued to be viable candidates for UAS operators. This argument was based on their ability to maintain situational awareness and make decisions within the ground control station user interface similar to the gaming environment with which they were most accustomed. While manned flight-trained

personnel may rely on other physiological sensing necessary in a manned aircraft to maintain situational awareness and detect changes, gamers did not require those types of clues. Triplett (2008) did, however, suggest that despite the benefits of a gaming background, UAS operators likely still need a basic flight background or understanding of the physics of flight and aircraft systems. Such relevant background experience would increase understanding of the performance of the aircraft, the time associated with inputs to the aircraft and the resulting response, and potentially help to mitigate any fictional effects introduced from any unrealistic gaming scenarios that shaped the gamer's experience. Depending on the level of automation, a thorough understanding of the aircraft systems and their performance may be critical to comprehending large amounts of information presented on UAS control station displays.

Lin et al (2015) evaluated gaming experience as a potential solution for manning shortfalls anticipated with increased UAS operations. Varying workload and levels of automation, Lin's team found that gamers were viable candidates. In particular, they highlighted that gamers relied on automation to a greater extent than pilots in higher workload conditions and during performance of a simulated weapons release task, resulting in lower stress. Additionally, they found that gamers with significant self-reported first-person shooter and action gaming expertise were more accurate in weapons release tasks (Lin et al. 2015).

The study by Pagan et al. (2014) examined the overlap and differences of qualifications associated with UAS and manned flight operations. A list of Knowledge, Skills, Abilities, and Other personal characteristics (KSAOs) for each group, was compiled and compared. Results suggested that 90% of the most critical manned flight KSAOs overlapped with unmanned KSAOs. However, the quantity of important KSAOs for each group was different, with 67 important manned KSAOs and 42 important unmanned KSAOs (Pagan, Astwood, and Phillips

2014). For reference, important KSAOs were rated 4.0 or greater on a 5.0 scale by manned and unmanned subject matter experts in an independent Job Task Analysis (JTA) conducted by Naval Air Systems Command (NAVAIR). Skills identified by Pagan et al. (2014) as not used for UAS operators included psychomotor skills, motivation, spatial orientation and mental rotation, among others. Accordingly, the primary manned flight skills of naval aviators tasked with flying UAS may be considered underutilized. This could result in the aviator becoming complacent or bored, and/or reporting less job satisfaction when operating UAS, a potential retention concern (Burke 2017).

Negative consequences such as human error may also occur as a result. Tvaryanas and Thompson (2008), for example, indicated that 50% of 95 UAS mishaps that occurred in the Air Force MQ-1 Predator community from 1997 to 2005 were due to human factor issues. Of these, 10%, or approximately five mishaps, could be contributed to latent issues such as motivation (of which complacency was a part).

5.5. Discussion

Online and PC gaming has steadily increased over the past several decades. Nielson (2018) estimated that 66% of the U.S. population plays video games while Statista (2016) estimated that 21% of home console gamers play more than 10hrs of video games per week. In consideration of the evidence from previous studies regarding the capabilities needed to operate UAS, perhaps there are two questions worth considering with regard to developing Navy UAS operators: (1) Should manned flight training be a requirement for UAS operators?; (2) Should gamers be prioritized for recruitment regardless of their (or lack thereof) manned flight training experience?

Similar to the studies by McKinley et al (2015), Wheatcroft et al (2017), Lin et al (2015), and Triplett (2008) that found gamers to be suitable candidates for UAS operators, the research outlined in Chapter 4 of this dissertation indicated that gamers and aviators performed similarly across several metrics when tasked with controlling and monitoring up to four Group 4 type UAS. The aviators used in this study were from Auburn University's Department of Aviation and averaged over 200 hours of civilian flight time as verified in their official Federal Aviation Administration (FAA) flight logs which exceeds the flight hours of both Navy flight school pipelines discussed previously. In addition to their undergraduate degree course work totaling 121 credit hours (Auburn University 2019), these students focused on the following flight qualifications during their four years of college: Freshman Year-Private Pilot Certification; Sophomore Year-Instrument Rating; Junior Year-Commercial Multi-Engine Rating; Senior Year-Certified Flight Instructor (Instrument). The cost associated with this training is published in the Auburn University Bulletin each year and is comparable to other university professional flight programs. In 2019, the total cost to train an undergraduate student aviator at Auburn University was approximately \$83K (Auburn University 2019). This does not include room and board and tuition associated with a student's undergraduate degree courses. In addition, Auburn University is one of a select group of institutions authorized to certify graduates with an Airline Transport pilot (ATP) certificate with reduced aeronautical experience (https://www.faa.gov/pilots/training/atp/media/Institutional_Authority_List.pdf).

As for if manned flight training should be required, the U.S. Army has demonstrated through their UAS training construct that manned flight training is not required for their Group 3 UAS and above. With the time to train for the Navy Fire Scout operators shown to be approximately two years for pilot designation, approximately one year for Fleet aircraft training,

followed by an additional two months for Fire Scout UAS training, the Army is providing UAS operators in less time than their Navy counterparts. Additionally, by removing UAS operators from manned flight training, the U.S. Army has removed the risk to the UAS trainee and the instructor that is inherent in manned flight syllabus requirements.

If manned flight training remains a Navy requirement for its Group 4 and Group 5 UAS operators, perhaps there are other alternatives to achieve the manned flight training that include truncated manned flight syllabi that do not include events that are not germane to UAS operations such as aerobatics and formation flight events. This could provide UAS operators more quickly, albeit without the flexibility to dual purpose these operators in manned aircraft. Additionally, there are civilian flight programs such as the program at Auburn University that graduates pilots after four years with an undergraduate degree and qualifications sufficient to pursue positions in the commercial flight industry immediately following graduation. This type of program may be worth consideration in providing UAS operators with a manned flight training at a lower cost to the Navy flight school model. Additionally, due to the attributes found in gamers, such as higher task engagement (Lin et al. 2015), less over confidence (Wheatcroft et al. 2017), faster visual search (McKinley et al. 2009), and others attributes common to the pilot population, putting gamers through a manned flight training syllabus may provide a highly capable UAS operator at a faster pace (McKinley et al., 2009).

Despite the potential advantages of these alternative recruitment and training approaches, dual-purpose aviators capable of flying both manned and unmanned systems clearly provide operational flexibility to the Navy. Another benefit to the model used by the Navy is that operators are able to maintain a diverse career path by moving between their primary manned aircraft and the UAS aircraft for which they were trained. This model also allows the Navy to

limit the manpower growth usually associated with the introduction of a new system. By dual-purposing existing pilots, the costs associated with adding UAS only personnel are avoided. However, as mentioned previously, the other armed services have taken a different approach to developing UAS operators, with some not even requiring manned flight training.

Dual-purpose aviators also eliminate the need of growing the Navy's total manpower force. Any use of UAS operators without manned flight training in the Navy would require an increase in personnel or an offset of personnel who are otherwise qualified to perform other missions. The former would come with substantial cost to grow and sustain the added force structure and the latter could come at the expense of manned flight readiness assuming the offset would come from the manned flight community. Neither of these are likely currently tenable. In addition to costs, there are logistical hurdles. For example, adding a UAS only operator to the current Fire Scout shipboard deployment model is likely not supportable due to berthing limitations on ships that hosts the Fire Scout. Nonetheless, it has been demonstrated through a variety of studies presented here that gamers have unique skills that make them viable candidates for UAS operations. It is prudent to consider gamers for UAS operators and alternatives to manned flight training as the use of UAS platforms expands and ultimately outnumbers manned platforms in the Navy's inventory.

5.6. Key Points

- The U.S. Navy is the only military branch that requires manned flight trained operators for Group 4 and Group 5 UAS.
- The U.S. Army and U.S. Air Force have shorter training requirements at lower costs for Group 4 and Group 5 UAS operators compared to the U.S. Navy.

- Manning shortfalls in U.S. Navy UAS operators are projected by the U.S. Government Accountability Office.
- Recruiting gamers and reducing manned flight training requirements may provide UAS operators more quickly to mitigate future manning shortfalls.

Chapter 6

Conclusions and Future Work

Automation is a critical component in many modern technologies. While automation is capable of reducing human workload, and, in some cases, may remove the human from the system altogether, it has also been shown to degrade human performance in monitoring and supervising tasks. Highly reliable automation has enabled, in some systems, the supervisory role of the human to shift from multiple humans monitoring a single system to a single human monitoring multiple systems. This trend of humans monitoring multiple systems will likely continue as computing power and machine learning techniques become more robust. Many CPSs may be particularly susceptible to cyber threats due to their frequent use of hard-wired or legacy communication connections.

Cyber intrusions may be intended to simply monitor system performance, or they could be more nefarious, such as to degrade the system to a point of failure. Humans must rely on timely and appropriate indicators from CPSs that should inform both automated and human responses to protect these systems. While research and action is needed to continually protect and harden CPSs, it can be assumed that once a vulnerability is removed, another will be identified and exploited by adversaries. Thus, it is prudent to consider how an intrusion impacts a human's performance when operating that CPS and how intrusions, anomalies, and/or adversarial actions may be identified.

Cyber intrusions may delay or inhibit timely and correct decisions. As was observed in this research, cyber events took significantly more time for participants to diagnose and respond to relative to "real" events. The cyber events also led to a higher percentage of human errors. The cyber events presented in this research were generalized as warnings that could not be

corroborated by expected accompanying information (e.g., a fuel pressure light without associated fuel level light). These events did not represent the myriad of anomalies and events that could arise. Nonetheless, it can be assumed, based on this research, that given a time-critical task to perform, an operator could become overwhelmed and unable to complete the necessary time-critical tasks if presented with numerous cyber events that require more time for diagnosis and response.

This is where automation may again come to assist. Future research could be conducted on alerts and warnings identifying that a cyber intrusion has been detected (and perhaps isolated) to an operator, permitting the operator to continue with the assigned mission. These alerts or warnings could be used to help improve the situational awareness of the operator and improve the operator's overall decision making. Questions exist as to how such alerts and warnings should be presented, as well as how they may impact performance, workload, and trust of the operator. Haptic cues or augmented reality may also assist in conveying information to an operator who is not collocated with the system that they are charged with supervising or controlling. Additional research may also be directed at identifying and evaluating the effects of alternative types of cyber events. For example, the risk associated with a loss of communications, false lights, spoofing, or compromised GPS likely differ. Are any of these easier than another for an operator to detect and respond to? It is also worth considering whether warning or cuing of cyber intrusions improves performance in real time or if it is better to use this information to train subsequent UAS operators so they are better postured to detect, diagnose and respond when such a situation presents itself. However, does this priming induce other errors or false diagnoses? Any cueing or priming of cyber events should be implemented only if it

improves operator performance in dealing with the cyber intrusion and should not be countered with errors on other properly functioning parts of the system.

Current user interface designs for UAS control stations differ from platform to platform and across military service branches. Not only are the software interfaces different, but the hardware is often substantially different with displays arranged in various configurations (e.g., horizontally vs. vertically; single screen vs. multi-screens). Many of those screen arrangements are not conducive to lengthy missions, as some head and neck positions cause increased fatigue, soreness and potentially degraded performance. Some are informed by legacy flight display models based on manned flight training and manned flight experience. Are these displays ideal for a generation that will have significant gaming background that may include virtual or augmented reality headsets used in personal computer and online gaming? It would be helpful to understand the limitations and benefits of different UAS control station designs on human performance. Taking best lessons learned from different control station layouts, optimizing the operator's time in the seat, and addressing ergonomic issues with operator posture could lead to better performance and job satisfaction for UAS operators.

A common user interface that could be applied across many different types of platforms is advantageous and presumably would result in lower costs and interoperability. Simplicity of user interfaces is also often advantageous to operator performance. If the design can be made so that training is minimized, then additional costs are saved by providing trained operators at a faster rate.

Finally, at the time of this research, the U.S. Navy is the only service that requires designated naval aviators, or manned flight-trained pilots, to operate Group 4 and Group 5 UAS. Other branches such as the U.S. Army and U.S. Air Force have separate qualifications for UAS

operators and do not require manned flight training in addition to unmanned flight training. Results of this dissertation indicate that gamers and aviators performed similarly in communication, contact identification, and real versus cyber emergency response tasks. If manpower shortfalls are expected in the future in dual-purposed naval aviators, or among dedicated UAS operators, then gamers may be a viable solution to mitigate risk across all of the military services. Additionally, re-evaluating manned flight training requirements could reduce time and cost to train UAS operators for the Navy.

It is the hope that this research encourages further research on the effects of cyber events on human performance in CPSs. Understanding the impacts will allow investigators and engineers to make informed decisions on corrective actions or mitigation measures. The application of this research extends beyond human operators of UAS and can be used in the design of future studies on similar human supervisory and control functions. The work presented in this dissertation was performed with this in mind: the human must be included in these types of systems and they must be able to make timely and correct decisions, as those decisions can result in life-or-death outcomes. This is certainly the case in UAS operations, but also in supervisory roles found in critical infrastructure and the industrial base.

Finally, regarding UAS operations, it is this researcher's opinion that instruments of war, which provide kinetic effects resulting in the intentional or unintentional loss of life, should require a human in or on the loop to make life and death decisions. If the human is removed from these decisions in favor of algorithms, machine learning, or artificial intelligence, regardless of the technologies' accuracy and reliability, then the cost of war is no longer a human experience. If the human is removed from these decisions, the impact of war will be less fully understood

and appreciated, making an entry into war, or an act of war, easier or even trivial. Such an unintended consequence should be unacceptable.

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Appendix A

Summary of True and Cyber Events that May Occur During each Scenario.

CYBER EVENTS		
ENGINE OIL PRESSURE LIGHT NO SECONDARIES	CYBER EVENT	Identify, Acknowledge, Corroborate, Report Fault. Oil Pressure Caution Light is on. Oil Pressure Gauge is normal/unchanged. Cyber event. EMERGENCY PROCEDURE - *1. Confirm with Secondaries. *2. No Secondaries Continue Flight. *3. Secondaries Present - Return to Home.
FUEL LOW CAUTION LIGHT NO SECONDARIES	CYBER EVENT	Identify, Acknowledge, Corroborate, Report Fault. Fuel Low Caution Light is on. Fuel Level Gauge is normal/unchanged. Cyber event. EMERGENCY PROCEDURE - *1. Confirm with Secondaries. *2. No Secondaries Continue Flight. *3. Secondaries Present - Return to Home.
5 GHOST TRACKS	CYBER EVENT	Ghost tracks will have no speed and no 3D image. Operator must figure out how to determine real from false tracks. Create track declutter button. In functionality this will only clear ghost tracks. If the operator notices ghosts tracks the declutter button will allow them to clear the issue. This button is only enabled after the ghost tracks appear.
GPS ERROR	CYBER EVENT	Identify and Corroborate Fault. Determine continuation of mission. Loss of link caused by GPS spoofing. Indications include comms/data status light, change in location (UAS over land maybe) etc. Situation is not resolved by internal/automatic link resolution. Link status goes yellow with initial loss for up to 30 seconds and goes red for next thirty seconds. Aircraft will attempt preprogrammed return home profile after 1 minute. This should not work because GPS has been spoofed. Aircraft should just fly off aimlessly.
FUEL PRESSURE CAUTION LIGHT WITH NO SECONDARIES	CYBER EVENT	Identify, Acknowledge, Corroborate, Report Fault. Caution Light Not Corroborated by Fuel Pressure Gauge Needle Still in the Green. Participant should keep aircraft on station. Participant should report (What, Cyber/Real, Return to Base/Continue). EMERGENCY PROCEDURE - *1. Confirm with Secondaries, *2. If secondaries, Continued flight NOT recommended -Return to Base. *3. If NO secondaries, continued flight recommended.

REAL EVENTS		
#1 Battery Current Caution Light	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. Caution Light Corroborated by #1 Battery Current Gauge at zero). No landing priority. Participant should report (What, Cyber/Real, Return to Base/Continue). EMERGENCY PROCEDURE - *1. Confirm with Secondaries, *2. Continued flight recommended. 3. Document issue at conclusion of flight.
#2 Battery Current Caution Light	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. Caution Light Corroborated by #2 Battery Current Gauge at zero). No landing priority. Participant should report (What, Cyber/Real, Return to Base/Continue). EMERGENCY PROCEDURE - *1. Confirm with Secondaries, *2. Continued flight recommended. 3. Document issue at conclusion of flight.
RADAR ALTIMETER FAILURE	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. RADALT FAIL ADVISORY LIGHT is ON. RED Ball light appears on ALTIMETER display. Real event. EMERGENCY PROCEDURE - *1. Turn Rad Alt On and Off. *2. Continued Flight Recommended.
LINK FAIL	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. Link status goes yellow on initial loss of link for up to 30 seconds. Link is regained through automatic relinking "algorithm" within 20 seconds of initial loss. No action required by the operator. EMERGENCY PROCEDURE - *1. Link Status Yellow - No action required. Monitor. *2. Link Status Red - Return to Home.
FUEL LOW CAUTION LIGHT with SECONDARIES	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. Caution Light Corroborated by Fuel Level Gauge Needle Low/"In the Red". Send Aircraft Home. Participant should report (What, Cyber/Real, Return to Base/Continue). EMERGENCY PROCEDURE - *1. Confirm with Secondaries, *2. Continued flight NOT recommended -Return to Base.
FUEL PRESSURE CAUTION LIGHT WITH SECONDARIES	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. Caution Light Corroborated by Fuel Pressure Gauge Needle Low/"In the Red". Also aligns with low fuel level. Pressure issues are more likely to arise in this condition. Send Aircraft Home. Participant should report (What, Cyber/Real, Return to Base/Continue). EMERGENCY PROCEDURE - *1. Confirm with Secondaries, *2. Continued flight NOT recommended -Return to Base.
ENGINE TORQUE SENSOR FAIL	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. Caution Light Corroborated by Engine Torque Gauge at zero. Engine RPMs, Temps and Pressures still normal. No landing priority. Participant should report (What, Cyber/Real, Return to Base/Continue). EMERGENCY PROCEDURE - *1. Confirm with Secondaries, *2. If engine RPM and Temp readings still normal, continued flight recommended. Document issue at conclusion of flight. *3. If engine RPM and Temp readings out of limits, return to base.
ENGINE OIL TEMP LIGHT WITH SECONDAIRES	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. Oil Pressure Caution Light is on. Oil Pressure Gauge Low/in the Red. Real Event. EMERGENCY PROCEDURE - *1. Confirm with Secondaries. *2. No Secondaries Continue Flight. *3. Secondaries Present - Return to Home. Operator should select to go home.
ENGINE OIL PRESSURE LIGHT WITH SECONDAIRES	REAL EVENT	Identify, Acknowledge, Corroborate, Report Fault. Oil Temp Caution Light is on. Oil Temp Gauge High/in the Red. Real Event. EMERGENCY PROCEDURE - *1. Confirm with Secondaries. *2. No Secondaries Continue Flight. *3. Secondaries Present - Return to Home. Operator should select to go home.