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Display Design to Avoid and Mitigate Limit Cycle Oscillations (LCO) on the F-16C

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THESIS

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Abstract

The U.S. Air Force F-16 Fighting Falcon's flying characteristics and flight envelope are dynamic and defined by its external weapon stores configuration. The employment of its munitions at certain speeds can put the F-16 into a flutter-like state in which Limit Cycle Oscillations (LCO) are induced. In LCO, a pilot's fine motor control might be hindered, and the aircraft may lose combat effectiveness until flight conditions are reduced. The current research attempted to provide pilots with a predictive feedback display to avoid an LCO-susceptible configuration by increasing their situation awareness about the consequences of employing certain munitions to their flight envelope. The current research also aimed to help the pilot recover from the LCO state, and whether a Status or Command display aid type was more effective. It was hypothesized that the predictive feedback display and recovery display would result in less flight envelope violations, less LCO occurrences, and faster recovery than without feedback. With the experimental display, a slight increase in situation awareness was present, but overall, the participant's combat performance suffered when the display was active. Feedback from participants indicated they liked the solution, but the design needed to be further matured.

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David J. Feibus

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DISPLAY DESIGN TO AVOID AND MITIGATE LIMIT CYCLE OSCILLATIONS ON THE F-16C

I. Introduction

Background

The F-16C Fighting Falcon made its first appearance in combat in Operation DESERT STORM in 1991, and the U.S. Air Force (USAF) has mainly used the aircraft for air-to-ground strike missions and to help establish no-fly zones, especially when engaging less than near-peer adversaries (U.S. Air Force, 2015). Initially developed to be a daytime lightweight air superiority fighter, the F-16 has evolved into a successful all-weather multirole aircraft. Thanks to the Service Life Extension Program (SLEP), the F-16 will continue flying until 2050 (Garbarino, 2018). In Operation IRAQI FREEDOM, air superiority was established within one month of the start of operations and no air-to-air kills happened within that timeframe. The last recorded combat kill by an F-16 with an AIM-120 Advanced Medium Range Air to Air Missile (AMRAAM) was 4 May 1999 during the NATO bombing of Yugoslavia (Haulman, 2016).

The F-16 is flown by the USAF and 26 foreign militaries. Since its first flight, its role has shifted from air superiority to a multi-role fighter, able to drop air-to-ground munitions and provide Close Air Support (CAS). It is considered one of the most adaptable airframes and has more than 3,000 possible certified external configurations. It is certified to carry numerous external stores (e.g., munitions, pods, and 3 external fuel

tanks). Each external store has a different mass, center of gravity, and drag profile. The combination of an entire loadout results in a configuration-specific flight envelope. This envelope is defined by a range of possible airspeeds, drags, roll rates, and the maximum g-forces, each of which influence the wing loading factor. After a munition is employed or jettisoned, the aircraft downloads into a "new" configuration which has its own flight envelope. For some configurations, if the envelope is exceeded, a turbulent state, characterized by sustained oscillations of the wings called Limit Cycle Oscillations (LCO), will be induced. This problem can happen to any aircraft in the fleet if certain flight conditions are present.

LCO causes the wings to oscillate, producing lateral turbulent motions of the aircraft in a way which can inhibit the pilot from controlling the aircraft effectively; degrading their ability to read displays, push buttons or precisely enter data. To eliminate LCO, the aircrew must change the characteristics of the airflow by reducing flight conditions, mainly airspeed. LCO can occur under multiple conditions but is particularly likely to occur after wingtip missiles, most commonly air-to-air AIM-120 AMRAAMs, are employed. This leaves the aircraft without mass on one or both wingtips to damp out normal oscillations, making the aircraft susceptible to LCO. LCO is "considered closely linked to classical flutter, except that the coupling of the structural response and the unsteady aerodynamic forces is nonlinear in nature, resulting in a limited amplitude oscillatory motion" (Bunton & Denegri, 2000). However, LCO is apparently non-catastrophic and no fatigue issues have ever been directly attributed to it. "LCO can occur in both level flight and during elevated aircraft load factor [g forces] maneuvers. It occurs

in the high subsonic to low supersonic speed regime" (Bunton & Denegri, 2000). A pilot must be mindful of their flight envelope for the duration of their mission to avoid LCO.

During training and today's primarily air-to-ground wars, wingtip missiles are always carried but are not employed, which leaves their mass to stabilize the wings in flight. F-16 pilots today have almost no experience flying without wingtip missiles and there is no specific alert system for LCO.

Unfortunately, because the pilot's experience during LCO is similar to the beginnings of classical flutter, which can compromise the structural integrity of the aircraft, untrained pilots may incorrectly infer the structural integrity of the aircraft is in danger and abort a mission prematurely. For this reason, there are concerns about the aircrew's ability to perform combat-related tasks while in an LCO condition, as well as the possibility that exposure to LCO during combat could persuade the pilot that something was wrong with the aircraft. This later conclusion might result in premature termination of the mission or a decision to avoid a part of the flight envelope crucial to combat survivability (Bunton & Denegri, 2000). Educating pilots about the signs and symptoms of LCO can only go so far; pilots must strive to stay within flight envelope restrictions to avoid LCO altogether, and if LCO is experienced, decide upon the best course of action to maximize combat effectiveness.

General Issue

In today's USAF F-16 fleet, improved indicators about LCO would be beneficial to guide pilots to appropriately alter their flight conditions. A lack of feedback ensures a

training gap exists as no corrective action ever needs to be taken during training, and pilots do not feel the importance of learning the LCO envelope restrictions.

In today's F-16 aircraft, pilots are asked to learn their specific flight envelope restrictions for that mission's loadout, plus the downloaded configurations' restrictions, and stick to them while also trying to simultaneously accomplish their mission and survive. To provide an example to which we can all relate from our day to day driving experience, this is analogous to remembering a change in speed limit where the permissible speed limit depends upon the radio station which is currently selected. Additionally, the manuals detailing the flight envelope restrictions are written to provide pilots with the maximum capability envelope rather than being written for simplicity. As a result, the restrictions are difficult to comprehend and during high workload conditions they are simply ignored by pilots, who will do whatever it takes to survive. Pilots experience high cognitive load during combat and this additional memory task further increases their cognitive load.

The F-16C Block 30/32 aircraft is equipped with 2 certified Primary Flight Displays (PFDs): a Head-Up Display (HUD), and a Central Display Unit (CDU). The HUD is used for generation and display of information in the pilot's forward Field-of-View (FOV). The HUD displays symbols associated with attack, navigation, weapon arming, and landing information, along with essential aircraft performance data such as altitude, airspeed, attitude, and heading. The CDU replaces the analog and steam gauges that were present in the early F-16s with a programmable interactive display. The CDU has a PFD, which displays the information from legacy gauges, and a Situational Display (SD). The

SD can display targeting pod video, datalink control, and electronic flight bag (e.g., runway approaches and document/image viewer) items.

The U.S. Navy's F/A-18 Hornet also experienced LCO in limited configurations but were able to upgrade their flight control system to avoid responses which caused LCO and since have eliminated the issue from their fleet. Due to the extensive nature of LCO throughout many configurations, such a simple fix may not be possible for the F-16 fleet, especially in times of budget cuts.

A pilot should and will prioritize mission success and aircrew survivability over the aircraft flight envelope; avoiding air frame fatigue and structural cracks do not matter if the aircraft does not survive. However, mission success is degraded by LCO as aircraft controls do not respond as normal and pilots have trouble reading displays or entering data. In today's aircraft, pilots can unknowingly trigger LCO, simply by being past the downloaded configuration's envelope limits and employing a munition. The download limits take effect as soon as the missile is employed, causing the airflow profile and mass characteristics of the aircraft to change. On top of this, a pilot may not recall their exact envelope or future envelope restrictions because it is a downloaded configuration from when they took off and have since employed or jettisoned munitions. Because of the interrelation between the triggers for LCO, recovery methods can vary, and a pilot must be aware of and recognize their situation to recover effectively to resume the mission.

Problem Statement

A common mantra for pilots and operators alike is to train like they fight. As these aircraft lack feedback in the cockpit under simulated and real conditions, pilots

cannot be effectively trained to avoid and recover from LCO. In the next near-peer war, air superiority may not be accomplished as easily as our previous wars, requiring the F-16 fleet to defeat enemy aircraft, putting the entire fleet at risk of LCO when they are required to deploy their wingtip missiles. A feedback mechanism to alert pilots if they are near the flight envelope limits or will exceed the downloaded configuration's envelope due to missile employment is needed. It may enable pilots to confidently select a bomb or missile to employ that is safe to operate within their current flight conditions or alert them of the flight conditions under which they will avoid LCO once the weapon is released.

Research Focus

This thesis focused on identifying methods to improve a pilot's situation awareness (SA), including projection of future aircraft flight envelope and state before they release weapons, potentially causing LCO. This research specifically focused on visual and auditory display designs which provide the desired enhancement, and by providing an appropriate combination of visual and auditory feedback to reduce mental workload and increase SA.

The primary case study for the visual display designs was the CDU, fielded on the Air National Guard F-16C Block 30/32. The visual designs were shown on the CDU screen and adapted to fit within the tactical needs of the pilot. Separate display designs were also developed for the HUD to provide the pilot with LCO feedback in their main display along with other important flight information.

Different feedback mechanisms might be necessary to predict a future LCO occurrence and to recover from LCO. Therefore, this research attempted to discover an appropriate mechanism for each potential LCO state. The purpose of this research was to create user-tested designs to be implemented in future F-16 upgrades to prepare the fleet for the next near-peer war.

Investigative Questions

1. What feedback mechanism results in quick comprehension of flight envelope state by pilots before and during LCO?
2. What Human Factors principles should a feedback system incorporate?
3. How does feedback about their present and future envelope affect a pilot's performance, including their ability to stay within the flight envelope during combat?
4. Can displays presenting future airspeed requirements to the pilot improve their SA?

Method

After a review of relevant research, an enhanced family of displays were developed, and a human subject's experiment was designed and performed. Designs were first conceptualized and iterated upon using Microsoft PowerPoint and graded by a select group of SMEs on the efficacy of information presentation and comprehension. The suggested design was then implemented in a low fidelity flight simulator to support human experimentation. An experiment was conducted which required participants to utilize data from the experimental interface and determined the effect of this interface on

the pilot's ability to perform combat tasks, avoid flight envelope violations, and improve their SA with respect to flight envelope restrictions.

Assumptions:

1. Everything in the F-16 envelope documentation is correct and valid for all altitudes and conditions. Not all configurations and envelopes have been flight tested due to the sheer magnitude of possible configurations and cost per test flight. The inability to change configurations in-flight led to F-16 engineers utilizing modeling and simulations to determine envelope limits, but these limits could differ in flight tests. Because this research primarily deals with designing feedback mechanisms, the underlying data must be assumed to be true, applicable across all F-16 aircraft for all conditions.
2. The resolution and aspect ratio of the designs are compatible with F-16 displays.
3. The design of this research was limited to the physical architecture of the F-16 and was based on changing as little as possible within the current construct. This includes the available displays, current graphical arrangements and interaction paradigms, and available data on which to base the display design. Other data may be available but on separate data busses, which would require future architecture changes. In this project, it will be assumed that this data set could be available to support the display interaction.
4. This research and its experiments focus on a specific air-to-air mission set for baseline SA, but results may vary for other missions, specifically air-to-ground missions.

Limitations:

A limitation of this research is the inability to fly the software designed in this effort and see how it truly performs outside of laboratory or simulator conditions. Due to COVID-19 setbacks in training pipelines, obtaining time in a certified simulator was not possible during this research. COVID-19 also reduced the ability of this research to find a larger set of qualified human subjects, and the sample population was limited to experts in the local Wright Patterson AFB area.

Implications:

Predictive feedback designs were explored in this research. The potential to significantly reduce the complex search and reference task of verifying the aircraft's conditions against the memorized envelope limits was reduced to a simple crosscheck item in this research. The results of this study will inform display designers of advanced human-computer interfaces for the F-16C.

However, this study not only applies to just the F-16C, but to any aircraft that does not currently have the capability to display or limit the safe flight envelope to the crew. The results of this research can help avoid in-flight errors such as overstressing the airframe that can ground the aircraft for weeks or longer. Especially in times of budget cuts where aircraft are asked to fly well beyond their service limit, keeping the aircraft within operating limits extends the lifespan of the airframe and saves the Air Force money in maintenance costs, inspections, and replacement parts. Keeping each F-16C airworthy lengthens the time it can be of service to our country.

II. Literature Review

Chapter Overview

This chapter reviews research pertaining to the enhancement and creation of fighter aircraft displays. This chapter begins with an overview of the development of displays to improve flight safety. A Cognitive Systems Engineering approach to the design of future displays will then be discussed, with Ecological Interface Design. This background will familiarize the reader with situation awareness and visual attention processes, as well as how they shape behavior and decision making. Relevant display design case studies will then be examined. Finally, the chapter will be summarized by examining the implications of this background for the design of displays to improve operator response to LCO.

Safety in Aviation

Excluding acts of terrorism, aviation accidents have decreased steadily and dramatically since the beginning of the 21st century. In 2017 there were no passenger jet crashes, making it the safest year in the history of commercial airlines (BBC News, 2018; International Civil Aviation Organization, 2020). Mandated system redundancies reduce the number of accidents from mechanical failures. Modern turbofan engines provide a level of safety and reliability that was unmatched by earlier piston engines. Inclusion of enhanced sensors with upgraded radar, weather, and navigational data have improved flight crew SA reducing aircraft accidents. Increased and recurring pilot training has made a significant, positive effect on aviation (AGCS, 2020). Over the years, aircraft have undergone many upgrades to present data more effectively, support pilot decision making, and aid operator response; often reducing the crew’s workload. These advances

are particularly notable in fighter aircraft, which often employ a single pilot crew who frequently have several responsibilities beyond the traditional air crew requirements of aviate, navigate, and communicate.

Every system has operating limits that, if exceeded, can cause damage and potentially failure. On certain systems this may be a temperature limit. For example, modern computers or cell phones will automatically shut off if the system is too hot to protect its internal components from damage. For an automobile, several components have operating limits that a user can monitor from the vehicle's dashboard, including engine temperature, oil pressure, speed, and revolutions per minute. Each of these gauges has markings to indicate the safe values for that parameter. Outside of these limits, a red line is often drawn on the gauge to represent the maximum parameter value at which the engine and its components are designed to operate. Straying into the area beyond the red line does not constitute immediate engine failure but may increase the chances of damaging the engine and often indicates that something is not functioning as designed. To prevent users from inadvertently pushing the engine past its limits when driving, modern car manufacturers install a type of governor to limit the maximum number of crankshaft revolutions per minute.

Similar concepts can be applied in aviation. A "flight envelope" in aerodynamics is defined as the operating bounds of an aircraft specified in terms of airspeed, maximum acceleration (measured in G's), and altitude of a specific aircraft. The aircraft and its components are designed to operate safely at any point within this envelope (Auld & Srinivas, 1995). If the aircraft exits the envelope in flight, stalling or overstressing the airframe can occur. Exceeding the flight envelope or flying in a way in which the aircraft

was not designed is often called flying “outside the envelope”. Operation in this regime can be quite dangerous. While operating outside the envelope does not constitute immediate structural failure, there are likely increased maintenance or sustainment costs.

This flight envelope is often specified in terms of a graph of speed versus load factor as illustrated in Figure 1 below. As shown the function on this graph provides a demarcation of safe and unsafe zones of performance. Load factors (g forces) are often the limiting design requirements for the vehicle. Speeds are determined by the aircraft’s handling performance and cruise speed. The external configuration of the aircraft also influences the airflow characteristics, and therefore affects the flight envelope restrictions. For fighter aircraft, the external configuration can include missiles, bombs, targeting pods, fuel tanks and their respective locations on the wing.

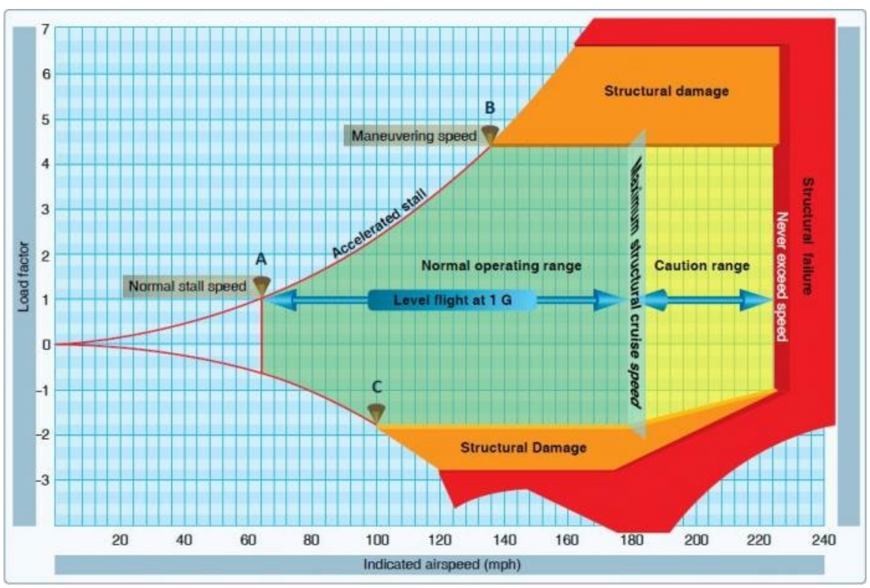

Figure 1: Sample V-g diagram, also known as a flight envelope (UAV Navigation, 2021)

Because the pilot needs to monitor and control several aspects of flight and their vehicle, cockpits are often full of flight instruments. Pilots are trained to apply an

instrument scanning method known as a “crosscheck” to maintain an up to date understanding of aircraft status while reducing memory requirements. This crosscheck permits the pilot to create a mental model of the aircraft’s state and update it regularly. An extensive amount of research and development has been performed over the lifespan of aviation to reduce the information acquisition cost through more efficient and effective flight instrument layouts.

Improvements in computing and information technology have led to incorporation of electronic displays in cockpits, commonly using Multi-Function Displays (MFDs). These displays, which replaced the legacy analog “steam gauges”, permit the pilot to select the information which is portrayed at any moment in time instead of using limited cockpit real estate for a single source of data. These electronic displays can be designed to present information in virtually any format which might be of use to the pilot. Newer technologies, such as HUDs afford the display of cockpit-relevant information such that the pilot does not have to alter their gaze from out the window (Curtis et al., 2010). Therefore, the HUD is designed to contain all flight-critical information and targeting symbology, allowing the pilot to maintain high SA of critical information without looking at the Heads-Down Displays (HDDs) within the cockpit. However, these HDDs contain supplemental information which is less time critical and may contain more in-depth details.

Safety on the F-16

Fly-by-wire (FBW) systems replace the cables between the pilot’s stick and the control surfaces on the wings with electrically controlled actuators on each control surface. The F-16 was the first production aircraft, commercial or military, designed with

FBW from the beginning. On FBW aircraft, there are Flight Envelope Protection Systems (FEPS), which are an extension of an aircraft's control system that prevents the pilot from making excess control inputs that would overstress the airframe (Abzug & Larrabee, 2005). The F-16 has the Flight Control System (FLCS) Limiter, which can limit the aircraft's maximum Angle of Attack (AoA) and forces resulting from acceleration according to the aircraft's gross weight, wing flutter, and external loadout. This system not only limits the pitch rate but also the roll and yaw rates to avoid overstressing the airframe. However, this system was designed to account for the weight on the wings to determine how much to limit the FLCS inputs, not the airflow characteristics. Therefore, it cannot limit the aircraft from entering LCO. As LCO does not cause physical harm to the aircraft, limiting the flight envelope of the aircraft to avoid this condition is not strictly required. Further, since LCO may arise from many possible causes, a system designed to avoid LCO on the F-16 through the FLCS may not fully succeed in its goal, which could be costly and cause pilots even greater workload.

Automated systems like the FLCS Limiter exist to aid the operator, including performing functions to lower the pilot's workload as performed by the flight computers in modern FBW systems. Automation can also help the pilot avoid dangers they cannot see or respond to, such as the event of g-induced Loss of Consciousness (G-LOC) which often precedes Controlled Flight into Terrain (CFIT) accidents. An example of the protection system for the latter case is the Auto Ground Collision Avoidance System (Auto GCAS). This system detects if the aircraft is on a trajectory common in CFIT accidents, takes control of and orients the aircraft to a safe attitude at a safe altitude. CFIT has caused over 9,000 deaths since the beginning of the commercial jet age and is the 2nd

leading cause of fatal general aviation accidents since 2001. Auto GCAS on the F-16 has saved 7 aircraft and 8 lives between 2009 and 2018 (U.S. Air Force, 2018). Systems like Auto GCAS are designed to work in cooperation with the pilot, enabling them to complete their mission while keeping their aircraft within safe conditions, ensuring pilot and vehicle survivability. With the systems and displays on the F-16 understood, the guiding principles of design for a new experimental display will be discussed.

Cognitive Engineering and Cognitive Systems Engineering

Cognitive Engineering is the application of "psychology and related disciplines to the design and operation of human–machine systems" aimed at improving system performance (Wilson et al., 2013). Through study of the operator in their actual work context, as well as in controlled environments, Cognitive Engineering combines multiple methods and perspectives to aid design, supporting the ultimate goal of improved human performance (Wilson et al., 2013). The system designer must understand the environment of the operator and the issues they will face to show how to make better choices and what the tradeoffs of those choices are (Norman & Draper, 1986).

Cognitive Systems Engineering (CSE) offers a "broader, systems perspective [of Cognitive Engineering] to the analysis and design of human-machine systems" (Hollnagel & Woods, 2006). CSE emphasizes the study of macrocognition, or the cognition of skilled operators working in actual sociotechnical systems. Macrocognition focuses on the emergent properties that become evident when the human cognitive system is situated in a larger system made up of both other people (socio-) and tools (-technical) situated in an environment (Wilson et al., 2013). The attributes of the environment in which the operator will use the system is incorporated into the design

iterations, as this can have a significant bearing on the functionality of the system as well as the desired or required output. Through this approach, "humans, technology, and work are analyzed as a joint cognitive system" (Hollnagel & Woods, 2006).

Ecological Interface Design (EID)

An important interface design approach of CSE is EID, which considers the affordances through which the operator can glean functional significance (Rasmussen & Vicente, 1989). EID principles state that interfaces should reveal the affordances of the work domain and support problem-solving. An interface should support an operator in the "execution of tasks, identification of problems, and afford their resolution" (Rasmussen & Vicente, 1989). Designs adhering to EID principles are best suited to effectively reduce serious mistakes that could otherwise lead to severe outcomes. EID is intended to facilitate the negotiation of errors through the operator's adaption to the system and environment (Vicente, 2002). Like CSE, EID focuses on the structure and constraints of the work domain and the affordances which that domain offers based on an operator's goals, instead of focusing on traditional cognitive constructs such as memory or attention (Endsley et al., 2007).

Traditional human-computer interface design techniques often assume a dyadic system during interface design, where meaningfulness is constructed from data presented in an interface. If this data is not displayed relative to its environment, the data can be ambiguous and lead to biased decisions. This leads to two people interpreting a situation very differently, such as reaching for the imaginary brake pedal when riding with a more aggressive driver (Bennett & Flach, 2011). In this construct, meaning becomes a construction of the mind, rather than based around the constraints of the system.

In contrast to the dyadic approach, EID proposes the use of a triadic approach to design that frames meaning in terms of the situation, rather than as a mental construct. The triadic approach to interface design helps facilitate the discovery of the meaningfulness of the situation through the affordances available to the user. This approach builds upon the supposition that there is a meaningful relationship between the human and its environment that is independent of the human's subjective beliefs or opinions (Gibson, 1979), where the consequences are independent of the human's opinion or belief (Bennett & Flach, 2011). Through the affordances of the system, the user can understand how their actions or inactions influence the system to meet their goals. By utilizing certain display techniques emergent features can be produced, i.e., higher-order visual properties that arise from the interaction of lower-level graphical elements. These emergent features are salient to the user and can provide decision support when displayed in the context using specific environmental cues (Bennett et al., 2008). This can be summed up through the ultimate goal of interface design, according to Bennett and Flach: "to help people to distinguish between those possibilities that are desirable and those possibilities that are to be avoided", as well as facilitating the discovery of the meaningfulness of the situation (Bennett & Flach, 2011).

A mental model is a dynamic set of concepts and the associations between them. They are how humans simplify complexity, why we consider some things more relevant than others, and how we reason. Mental models allow us to process an information-rich environment and turn it into easily understandable and organizable chunks. Users develop mental models of how they think the system works through training as well as interaction with that system (Norman, 1988). Mental models in human-computer interaction are

defined as the operator's "understanding of behaviors of the system and themselves", which helps them evaluate the system's current state, predict future behaviors, and troubleshoot failures (Takano et al., 1997).

In complex environments, operators must both gather data about their environment and interpret that information to prioritize critical data points (Shobe et al., 2004). Training and interaction with a system is required for development of a complex mental model. More experienced operators will have more refined mental models than novices, allowing experts to understand conceptual linkages similar to other experts. Through tools such as iconic cues, an operator's attention can be captured to changes in the system, enabling faster diagnosis and response to issues (Wilson et al., 2013). Information prioritization is particularly important in complex, task-intensive environments.

From the design principles of CSE and EID discussed above, the basis for an effective display designs can be developed. Any solution made that correctly utilizes these principles will prioritize helping the user understand their influence on the situation and its consequences, which is required for pilots to understand how their mission goals are affected by their LCO limits.

Situation Awareness (SA)

SA can be defined as the "perception of the elements in the environment, comprehension of their meaning, and projection of their status in the near future" (Endsley, 1988; Endsley & Garland, 2000). This attribute can be operationalized in terms of an operator's goals and decision tasks for that job. SA, mental models, and goals are

updated in a cyclic process, in which perception directs attention, comprehension matches patterns to mental models, from which projections can be made about the future state of events towards the user's goals. Using mental models from long term memory reduces the demands on working memory – but this can lead to problems with biasing in the selection and interpretation of information which may create errors in SA (Fracker, 1988).

According to Endsley, there are three levels of SA that contribute to decision making (Endsley, 1995). Level 1 is the perception of elements in the current situation (location, altitude, current target). Level 2 is the comprehension of the current situation through synthesis of Level 1 elements (mission timing and status, impact of system degrades, tactical status of threat aircraft). Lastly, Level 3 is the projection of future status based on Level 2 elements (projected aircraft tactics and maneuvers, firing position and timing).

SA is commonly measured through queries or probes, in which the experiment is paused and one or more questions about the state of the task or environment is asked before resuming the experiment. The probes are based around elements in the scenario deemed to be important for understanding and projection by experts. The response accuracy provides a measure of SA. The same question can be asked multiple times in a scenario to track an operator's SA over time. The most popular query method is the Situation Awareness Global Assessment Technique (SAGAT) (Endsley & Garland, 2000). Query methods can be used in combination with either measures of the performance of the experimental task (deviating from a flight plan), or subjective measures by the participants of their SA level (Durso & Alexander, 2010).

Pilots may experience LCO because they do not have SA of their situation or their aircraft conditions, which can be caused by the increased workload of combat. To understand how to support operator SA, the perceptual system must be understood.

Perception

To create SA and shape mental models, humans utilize perception to process information from their environment and make decisions. The sensory systems that make up the eye and ear are critical for successful and effective perception.

When light is directed at the eye, it enters through the cornea, iris, pupil, and then the lens, which control how much light is allowed in and focuses the light onto the macula region of the retina which is then converted into electrical signs for the brain to process. Inside the retina are photoreceptors called rods, responsible for monochrome, low spatial acuity vision at low light levels, and cones, which produce higher acuity, color perception at higher light levels. The macula can be subdivided into the foveal and parafoveal areas. A small pit of densely packed cones, the fovea, is responsible for sharp central vision needed for activities in which high visual detail is required (Proctor & Van Zandt, 2008). Due to the size of the fovea, the resolution of our eye is greatest within the 2-degree center of our eye (Miller, 2019).

Outside of the fovea, in the parafovea and periphery "resolution and color sensing capability decreases eccentrically as distance from the fovea increases" (Miller, 2019). Eye movements can be characterized by two main components: the fixation and the saccade. A fixation occurs when the eye dwells on a single area of interest to obtain information about that area. A saccade is used to move between fixations, commonly

characterized as discrete, “jerky movements” that direct the fovea to an object or region of interest (Wickens & Hollands, 2000).

The sense of hearing plays an important role in the communication of information, commonly used to alert the operator to potential problems, such as leaving the key in the ignition or that the turn signal is on (Proctor & Van Zandt, 2008). The human ear acts as a receiver for sound waves that are collected by the outer ear, directed into the auditory canal, and produce physical movement of the eardrum. This motion is transferred to the bones in the middle ear, which transfer that motion into the cochlea which contains tiny hair cells that respond to the movement to create electrical signals (Proctor & Van Zandt, 2008).

With an understanding of our perceptual system, a perception theory can be discussed. Neisser’s Perceptual Cycle Model (PCM) takes an ecological approach to perception, emphasizing the role that both mental models or “schemata” and environmental information play on shaping actions and decisions (Neisser, 1976).The PCM utilizes both top-down and bottom-up processing to explain perception, where mental models are “triggered by contextual conditions, direct perception, and behavior, thus interaction in the world” (Plant & Stanton, 2015). Environmental information has a modifying and updating effect on mental models, which influences further interaction through top-down processing. After the interaction with the environment, the cycle repeats as the human then perceives the environment’s change in response to that interaction, which influences future behavior. “Cognition is extended beyond the individual because behaviors are grounded in the context of the environment in which they occurred” (Plant & Stanton, 2015). The PCM can be considered a human-centered

systematic approach to the study of cognition and action, because schemata are person-specific mental models; no two people will ever have precisely identical schemata because they will all have different past experiences (Neisser, 1976).

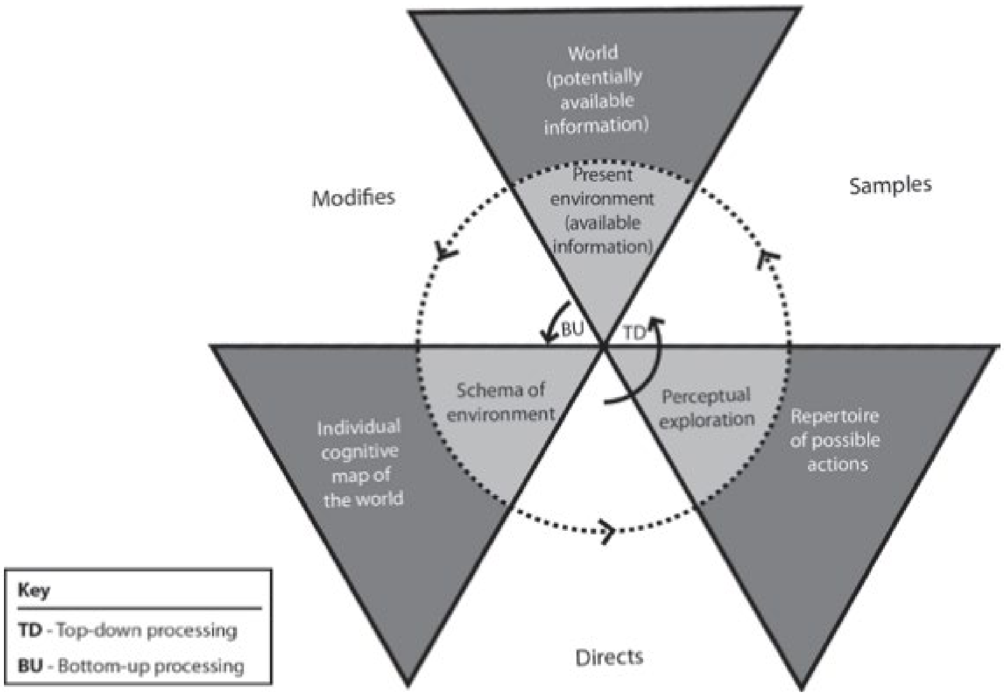

Figure 2: Perceptual Cycle Model diagram showing the cyclical process of observing the world, exploring it, and observing the consequences (Plant & Stanton, 2015).

Perception theories like the PCM play a key role in informing how displays should be designed to support SA, especially when considering how to show the user that changes in the situation have happened, or when choosing how to present situational elements in the display. In one study, 76% of SA errors could be traced back to "problems in the perception of needed information" (Jones & Endsley, 1996). Displays support mental model creation by ensuring proper perception takes place and

understanding how a person will create their mental model of the situation is important to provide sufficient knowledge to the user.

Comprehension

SA also encompasses how people integrate, interpret, store, and retain information. The integration of multiple pieces of data through pattern recognition, interpretation, and evaluation enable the determination of their significance on the person's desires or goals (Endsley & Garland, 2000). Pattern matching allows for rapid understanding of a situation, which can help shorten the decision-making process. The perception of near-threshold environmental cues is an important factor for effective pattern matching (Hartman & Secrist, 1999). A person who can derive operationally relevant meaning from elements perceived in the environment has an ecological understanding of their environment and can mitigate issues easier.

Errors in perception lead to incorrect mental models, which can impact the entire decision and fault management process and hinder a user from correctly projecting the consequences of their actions. Spatial disorientation has been blamed for 20% of all fatal mishaps in military aviation and "is a large factor in many high-profile civilian accidents" (Previc & Ercoline, 2004), such as the CFIT helicopter crash in 2020 which killed Kobe Bryant. A pilot's perspective with respect to the gravitational vector is always changing, and so the human vestibular system is challenged, which can lead to dangerous illusions and misjudgments when not enough visual context is present. In early aviation, flight instruments had to be created to afford direct perception – pilots often attached a streamer or string on their wing to see the direction of the relative wind (Vidulich et al., 2010). This provided knowledge of the state of the aircraft relative to the Earth, creating a

mental model of the aircraft by integrating the multiple sources of direct perception data to form one coherent picture.

Comprehension is the second step in creating SA, and the knowledge gained from this step can be built upon for decision-making. However, errors in comprehension can lead to faulty decisions, especially if the environment is not well understood or perceived.

Projection

Given knowledge about the environment and how the perceived elements interact dynamically, projection is the process of using that information to forecast future situations and predict dynamics of events. The ability to anticipate future events and their implications is important to support decision making.

After perceiving the environment and comprehending the situation, a pilot will decide to act based on their projected future state, and then observe the consequences in relation to their desires and goals, at which point the cycle starts over, as defined in the PCM. For example, if a pilot notices both their airspeed and altitude decreasing, they can comprehend they are flying too slow and project that an increase in throttle will mitigate the situation. Errors in projection can be caused by improper expectations based on past experience and can lead to disastrous consequences (Endsley, 1995).

To understand if their actions will induce LCO, a pilot must, before deploying a munition, project their future status after a munition has been employed. By using the data perceived from their flight instruments, a pilot needs to know if their actions will place them into danger. Improper projection leads to wrong decisions, and consequences for those decisions, such as LCO.

Decision Making

Pilots often must make rapid decisions and perform dexterity-intensive procedures in the presence of huge amounts of data from sensors, threats, wingmen, and more to ensure their survival and mission success. Wrong or late decisions can have fatal consequences, which further increases the high cognitive and physical workloads of the pilots (Helldin & Falkman, 2012). While accidents in safety-critical systems are rare and low probability, they have an extremely high cost if they are realized (Stanton & Walker, 2011).

The PCM and Endsley's model of SA can be used to evaluate decision making, because it acknowledges the distributed cognition through the interaction between mental models and the environment (Endsley, 1995). Plant et al. divide the process of dealing with a critical incident into three phases to understand what processing is taking place and when: Onset of problem phase, Immediate actions phase, and Decision-making phase (Plant & Stanton, 2015). The onset phase is characterized by bottom-up processing using the physical cues or conditions that alert the pilot to the problem (perception). In the immediate actions and decision-making phases, the researchers suggested that both bottom-up and top-down processing are occurring – using environmental information and stored knowledge for incident assessment (comprehension and projection). Lastly, the decision-making phase uses that internal knowledge and once the action is completed, receives and processes feedback from the environment to know if the problem has been resolved (Plant & Stanton, 2015).

Decision Support Systems

A decision support system (DSS) is about pairing the best characteristics of both man and machine to improve the quality of decisions (Keen & Scott Morton, 1978). In certain systems, a DSS can process the data required to make a decision that may be too large, dynamic, or complex for a human to effectively comprehend and can provide a way forward. The user interface of a DSS can take various forms, depending on the environment of the system.

Two notable types of decision aids from the user interface are Status and Command displays. Status display alerts user to need for a decision, or a change in status to aid the user in recognizing an impending problem. Command displays instruct the user to take an action in response to a detected impending issue. The time pressure of the decision plays an important role in which type of display should be used. For decisions that are under extreme time pressure, a Command display should be used. However, incorrect information from a decision aid negatively impacts decision making capabilities, so if the DSS has low reliability or the users prefer to stay in the decision loop, a Status display should be used.

Fighter pilots depend critically on decision support to help them assemble evidence from several input sources, assess the situation (i.e. threats), and evaluate the significance with respect to their mission and opponents' capabilities (Svenmarck & Dekker, 2003). In threatening situations, the role of the support systems becomes even more central because the pilots need help assessing the situation and prioritizing tasks to accomplish the mission (Helldin & Falkman, 2012). Decision support systems have been developed across the world, with some trying to offer solutions, and others aimed at

supporting the operator's situation assessment. A decision support system should "aid a pilot to balance the three objectives of flight safety, combat survival, and mission accomplishment" (Helldin et al., 2010).

Mental Workload

Mental workload has been defined as the relationship of the available mental capacity a user has to complete tasks and the attentional resources required to complete a task (Parasuraman et al., 2008). Mental workload can contribute to pilot or controller error and increase the potential for error if it is either excessively low (under-stimulation) or high (overstimulation) (Durso & Manning, 2008), the consequences of which can have inherent safety implications. On the flight deck, workload can be decreased through the implementation of technology combined with effective human factors design, resulting in a reduction of the number of personnel required as well as to reduce the workload of individuals on the flight crew. An example of the latter are fighter planes that historically required two pilots now only need one (Durso & Alexander, 2010). Workload is driven by variables such as "task difficulty, concurrent tasks, operator training, and the temporal demand associated with tasks" (Wickens, 2008). Task demand can result from either single-task demand such as flying a complex approach, or dual task demand, such as having to communicate with ATC during the task (Wickens, 2008).

Designers trying to have their alerts noticed more than other alerts puts the pilot at risk of sensory overload, a condition that will cause information loss, fatigue, and stress to the already overworked pilot. Endsley's "Information Gap" highlights the disconnect in that presenting more data and information does not necessarily correlate to more understanding and information but can in fact hinder understanding (Endsley & Garland,

2000). The “Data Availability” paradox is that designers and users recognize the importance of having the maximum amount of data possible to avoid missing any critical information, but also that it is impossible to interpret a flood of data and so less data may need to be presented (Woods et al., 1999). Attentional capture will be discussed later.

The level of workload experienced impacts the amount of SA available to the pilot at any given time (Endsley, 1993). A pilot in an overload condition will expend a lot of mental effort toward task management at “the expense of observing and perceiving the environment around them” (Meyer, 2015). This mode of operation has been termed “scramble mode” (Hollnagel & Woods, 2006). While SA and workload can vary independently, Endsley found that outside of an overload condition, motivated operators can achieve high SA with acceptably high workloads (Endsley, 1993). SA and decision making are interrelated, but “it is entirely possible to have perfect SA and still make the wrong decision” (Endsley & Garland, 2000) due to inadequate training, strategies, tactics, or other constraints.

The linkage between mental workload and SA is important to recognize for this application because during combat, pilots are usually heavily task saturated and they are focused on certain displays and conditions in the aircraft. With this increased workload, less SA is potentially available for perception of peripheral elements, usually where alert displays are placed. When necessary, an alert system needs to be able to pull the pilot out of this state to focus on higher priority information. Understanding this attention deficit allows different modalities of alerts to be compared to each other.

Visual Attention

With all the information that is presented in the cockpit, a pilot needs to know where and when to look, and how to find information they need among the distractors. Not all stimuli in the visual field can be processed at once, and so humans rely on visual attention to control the selection of a subset of a scene. To shift visual attention, a source of guidance is required, drawing from information in the periphery to drive changes in fixation location and attention (Wolfe, 2010). These features can be color, size, motion, and others. Sounds can drive our visual attention as we look to find out what made a noise when the object is in our visual periphery. Once fixated on the area of interest, scene perception uses both "foveal and peripheral visual information, sensitivity to which varies with retinal eccentricity" (Loschky et al., 2005).

Attention characterizes the "limits of processing information about multiple tasks and their perceptual cognitive elements" (Vidulich et al., 2010). These elements can be things such as objects in the environment such as symbols on a display, thoughts, ideas, plans, or tasks and goals. Based on their goal or agenda at the time, a pilot will utilize certain instruments over others and designers must be cognizant of this to understand how to break that focus and attract the attention of the pilot if a higher priority piece of information must be communicated. By using selective attention techniques, pilots can process necessary information and maximize the efficiency of their attention, perception, and search processes. Pilots look to where they expect to see dynamic changes, driven by the concept of expectancy.

Cognitive or attentional tunneling, a phenomenon in which a pilot's attention becomes too selective, can stem from elevated workload conditions, and result in a pilot

ignoring information outside of their current focus (Dirkin, 1983). This is similar to pilots halting tasks to focus their attention on a higher priority task, and forgetting to resume the dropped task – a frequent example of a dropped task is "altitude monitoring, whose abandonment can lead to CFIT accidents" (Vidulich et al., 2010). This is another added benefit of automation such as Auto-GCAS: it picks up the tasks, such as ground collision avoidance, that may accidentally get dropped while trying to engage a target. Too much clutter on flight displays has been linked to cognitive tunneling, requiring pilots to sift through large amounts of data and taking their attentional resources away from other flight-critical tasks (May & Wickens, 1995).

Though salient events may grab a pilot's attention, cues that are not as visible but just as important, such as downward trends, can be filtered out by change blindness (Stelzer & Wickens, 2006). Alerts that capture an operator's attention to inform them of critical information must be integrated within the context of that environment. In dynamic or data-rich display environments, flashing notifications do not necessarily have the same attention-drawing capability as less noisy environments (Nikolic et al., 2004). The process for capturing a pilot's attention is inherently bottom-up, and the farther away a pilot's attentional focus is from visual alerts, the less likely they are to notice the appearance of a mode change or alert. Color similarity, movement of surrounding display elements, and target cue eccentricity all contribute to the difficulty of capturing an operator's attention, taking them away from their currently attended task (Nikolic et al., 2004). This is particularly true when can be cognitively tunneling occurs, reducing the operator's functional field of view and making it more difficult to extract information from the periphery (Rinalducci & Rose, 1986).

Understanding how to attract a human's visual attention to alerts is an important facet for any new visual design that must communicate important information to a potentially task-saturated user. In a safety-critical situation, alert information must be properly prioritized so that a user can mitigate issues that arise without being overwhelmed.

Feedback in the Cockpit

This section will detail how some interfaces were designed around EID principles to provide the operator with greater SA of how they can influence their environment, as well as some examples of interface design that did not support the user. As stated above, the goal of EID is to create visual designs that align to the dependencies and interactions of functional processes in the operator's environment. Under EID, displays should support effective decision making and problem solving. In their design of the "Total Energy-Based Flight-Path Display", Flach et al. aimed to help pilots understand how their control inputs on the throttle and stick influenced the overall aircraft's energy available during landing. Using visual cues, pilots could understand their energy deviations from the optimal glide slope and the means to correct them (Bennett & Flach, 2011). By mapping the control functions to a higher abstraction of "energy level", the pilots could recognize and complete higher-level goals through low level functions, utilizing less processing, increasing SA, and reducing mental workload.

During the Space Shuttle's operational years, an upgrade program to the display formats designed to reduce crew workload and improve SA was developed, but never integrated before its decommissioning. Using the modern concept of data fusion, the displays aimed to reduce the acquisition cost to process critical information (Ferguson &

Thompson, 2006). Using 11 different colors, designers afforded operators the potential ability to use parallel search techniques to find errors instead of scanning through a matrix of seemingly homogeneous data (McCandless et al., 2005). By drawing an operator's eye rapidly to the problem, a user will experience less mental workload to absorb new information and can react to the issue faster, saving critical seconds.

An alert system exists to provide failure information about the vehicle systems to its operator, and therefore should convey the root cause of the issue to support the operator to fix it quickly (Hawkins, 1993). Designers also incorporated spatial relationships to allow users to "see through" the displays to discover the issue with an underlying system (McCandless et al., 2005), providing at a glance indications of the operational status and mode of the subsystem. By affording users to create a rapid understanding of any system they query through the display, it becomes a useful tool instead of a thorn in an operator's side.

A glass cockpit also affords source integration, or the combination of multiple sources of data into one screen such that an operator does not have to incur the search cost of collecting the data from all around the cockpit. However, to actually address the workload caused by manual data fusion while also reducing visual scan time, type integration must be utilized – overlaying similar types of information onto the same display space simultaneously (Curtis et al., 2010). Using type integration in combination with the "Proximity Compatibility Principle" can yield effective results, but also issues with clutter if too much information is presented in the same space (Wickens & Carswell, 1995). Integrating subsystem data in a dedicated space on a display reduces information processing costs as operators can better understand the context where that system resides.

Presenting information in pilot's field of interest is optimal, as a pilot is less likely to crosscheck an instrument where head rotation is required than to the HUD (Wickens et al., 2007).

The display's context influences the monitoring and interpretation of each individual display element and alert, and while some alerts may appear to be effective representations of the underlying data, "effects of color similarity, movements of surrounding display elements, central task difficulty, and the eccentricity of the target cue" must all be considered when evaluating their integration (Nikolic et al., 2004). While bottom-up processing plays a large role in an alert capturing the operator's attention, top-down processing also plays a considerable role in modulating attention capture and guidance (Pashler et al., 2001). While many displays use color to draw attention such as in the Space Shuttle case study, Nikolic et al. found that "changes or movements of surrounding display elements are more powerful than color similarity in mediating attentional capture" (Nikolic et al., 2004).

The research discussed within this thesis used the design concepts from these case studies to inform the experimental displays to avoid and mitigate LCO. However, the new display was also required to operate in the background due to the secondary nature of avoiding LCO and was required to mitigate nuisance alerts.

Literature Implications for LCO

The current lack of alerts or warnings for LCO provides a system in which the pilot has inadequate information about the state of the aircraft in relation to its flight envelope. This is particularly true prior to entering an LCO state, but even during LCO,

the pilot can attribute oscillations to other sources, such as turbulence. If the pilot is unaware LCO was about to happen, their mental model of the aircraft appears accurate prior to LCO but completely incorrect once the aircraft enters LCO. This inability to perceive their status with respect to LCO, understand its implications, and project the future state of their aircraft is a complete breakdown of SA. A spike in workload of having to deal with unexpected LCO is likely to result, as well as a disruption of their SA.

Having a feedback system to warn about LCO is crucial to preserving SA and maintaining a correct mental model, allowing the pilot to project their future status effectively. However, if the feedback is not salient and the pilot's attention is focused elsewhere, they could miss the warning and enter LCO unknowingly, even if a system is in place. The examples in the previous section demonstrate how feedback and EID principles can increase the SA of the operator and reduce their overall workload, resulting in higher performance, effective mental model creation, and overall satisfaction with the system. To properly design a display to help pilots avoid LCO, all the topics discussed above must be considered, including EID, SA, decision making, mental workload, and visual attention.

III. Methodology

Overview

The research included a design of the experimental displays based on interviews with SMEs, and an experimental component. Each will be discussed in detail in this chapter, with the results of the design and the experiment in Chapter 4.

Display Design

Information Gathering

The first stage in the design method was to understand the phenomenon of LCO, its main contributing factors, and to define what a pilot can do to fix or avoid the situation. Through extensive interviews with SMEs from the 40^{th} Flight Test Squadron at Eglin Air Force Base, a concept map was developed, seen below in Figure 3. The SMEs indicated that experiencing LCO without a fast recovery path during combat could be a deadly combination. Thus, avoiding LCO entirely during combat is the desired option. The loss of fine motor control which occurs during LCO degrades the pilot's ability to target adversaries. The Concept Map in Figure 3 shows that there are multiple factors that can place an aircraft into LCO, such as airspeed, Mach number, altitude, g forces, and more. For a pilot to track these conditions given limited working memory while task saturated or experiencing high stress and workload conditions can feel like an impossible task, especially during combat. These factors include in-flight configuration changes due to weapon employment which causes changes in the airflow around the aircraft, potentially changing its flight envelope limits.

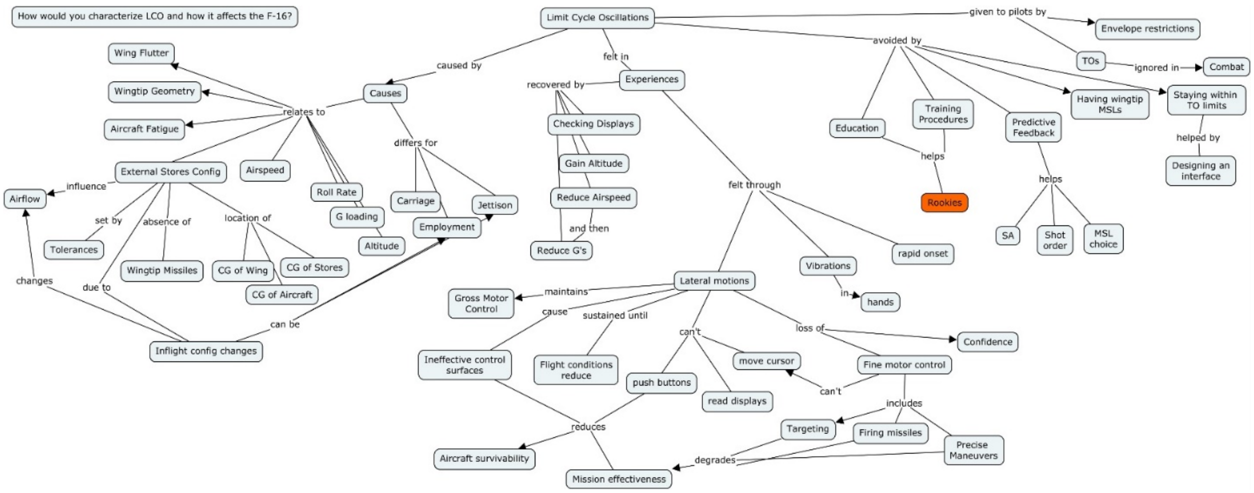

Figure 3: Concept Map developed after SME interviews. The "Rookies" bubble is highlighted because the SMEs communicated that rookies/novices are the most at-risk of LCO and its consequences.

All of the pilots interviewed expressed that the envelope restrictions in the TO cannot be quickly understood and are often confusing, leaving most pilots unable to adequately understand the consequences of each weapon's employment on their flight envelope restrictions. Further, the implications of these dynamic limits must be memorized prior to the mission or reviewed in real time during the mission, which can be too time consuming. The Concept Map in Figure 3 revealed that pilots need a way to recognize that they are susceptible to LCO either because of their current configuration and aircraft conditions, or that they will become susceptible to LCO when they employ a selected weapon. Without advanced warning of LCO, a pilot could increase LCO by employing a wingtip missile. Currently, pilots must manually do the math and compare the airspeed and Mach number based on their weapon stores remaining to memorized or written restrictions to understand if their next weapon release will result in LCO. The

Concept Map in Figure 3 revealed that giving pilots advanced knowledge of their future condition may help them avoid LCO, or at least its onset will not be as surprising.

All pilots interviewed expressed that any system developed to help prevent LCO occurrences must operate in the background and should not require too much of a pilot's attentional resources. They desired a display that could be quickly crosschecked, permitting them to verify that their next action will not introduce unacceptable levels of LCO. Because LCO is not a safety-critical phenomenon, any display or feature designed to counteract or avoid it must help the pilot remain combat effective. The display must maintain tactical options but help the pilot avoid overstressing the airframe or inducing LCO. The LCO Support system must not take up too much real estate on the displays and must not block vital information. The interviews also revealed that most pilots, especially rookies, have not experienced LCO and would be unaware of how to recover from it if experienced. This is especially true while the pilot is task saturated or in combat. Flight condition trends were initially of interest to the pilots, but this idea was discarded as the pilots wanted a simple answer if they were out of bounds. Wing loading (g forces) was also initially included in the design, but airspeed and Mach number were eventually prioritized.

Based on the interviews, the following design goals were created: 1) As Norman suggests, take the TO limits out of the pilot's head and put it into the world, allowing pilots to know at a glance if they are in bounds or not (Norman, 1988). 2) Use the coactive design concepts of observability and predictability to give pilots predictive feedback telling them that if they employ the current munition, they will either be in LCO or their envelope will change, based on their current flight conditions (Johnson et al.,

2014). 3) Help pilots recover from LCO or flight envelope violations quickly through the coactive design concept of directability (Johnson et al., 2014). Based on the design goals, the display design was decomposed into Predictive Feedback (PF) to be provided before the pilot takes actions which are likely to induce LCO and LCO Recovery (LR) which is provided after the pilot takes actions which are likely to induce LCO or violate the flight envelope. The development of the LR display will be discussed in the next section.

Predictive Feedback (PF) Design

From the design goals, information requirements emerged for the PF display. Airspeed and Mach number, plus their external weapons configuration, play the largest role in an aircraft's susceptibility to LCO. A pilot needs to know their aircraft's flight conditions, their current envelope limits, future envelope limits depending on their currently selected munition, and if they are at risk for LCO. A pilot must be able to periodically and easily crosscheck those values to know if a change in flight conditions is needed. The display must also be useful when the pilot is highly task saturated, or if fine motor control, including fixation on displayed text, is lost due to vibrations from LCO reducing the legibility of the displays. Pilots also expressed an interest in knowing the state of their external stores at a glance, allowing them to quickly make the decision to step to another missile to avoid LCO or maintain missile symmetry.

The location of the LCO indicators on the display was an issue as well. Ideally, an indicator of LCO would be available in the HUD, similar to all other important flight information. However, any software update to the F-16C's Operational Flight Program (OFP) would take years to come to fruition, mainly due to the high cost and complexity of an OFP upgrade. The moving map page of the CDU became a perfect target for the

new display as is it not classified as a "Primary Flight Display". The CDU is an ideal candidate for this research as the CDU has its own processor and can host 3rd party software without modifying the safety-critical aircraft software, also known as the Operational Flight Program (OFP). Therefore, it would be much easier to change if this design was to be fielded.

Within the moving map page, the location of the display was suggested to either be at the bottom or top of the screen. Given that the seat of the F-16C is reclined at 30 degrees, the top of the CDU is essentially between the pilot's knees. Both locations, top and bottom, were intended to be tested. However, after a mockup was placed in an F-16C simulator, it was determined that with a helmet and oxygen mask on, the bottom half of the CDU was obscured and would not provide even a peripheral alert while the pilot was heads up. Any alerts presented at the bottom of the CDU would require head movement to see them. Given that the pilot is experiencing turbulent lateral movements during LCO, moving the head downwards to read or check data at such an angle would be difficult and distract their attention from the PFDs in the HUD. Also, the turbulent motion induced by LCO disturbs the vestibular system, making displays farther from the resting visual angle of the HUD difficult to read. Thus, it was determined that the top of the CDU's moving map screen was an ideal location for the display.

After multiple design iterations and feedback from test pilots, a PF design was developed that showed the participant several details about their aircraft's status, including: their external stores loadout, the current weapon selected, and their envelope limits, which was comprised of the maximum allowed Knots Indicated Air Speed (KIAS), and the maximum Mach number on the right side of the display. The PF display

also showed the pilot their download envelope limits based on the current weapon station selected that would take effect when the currently selected missile was employed. The dynamic download limits were shown on the top left using "DWN" to identify them against the current envelope limits on the right side of the missile bar. A sample graphic of the CDU is shown below in Figure 4.

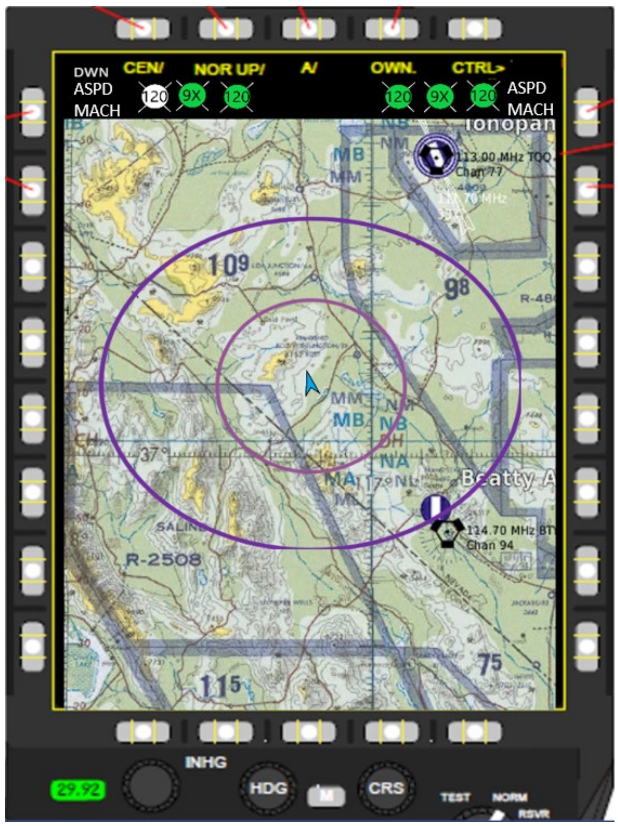

Figure 4: The Predictive Feedback display at the top of the CDU TAD page, with the moving map and range rings. The left Airspeed (ASPD) and Mach are the download envelope limits (DWN) and the right values are for the current envelope. The currently selected missile is shown in white. The labels for the CDU Option Select Buttons (OSBs) were not shown because the buttons were not functional.

For the experiment, other than the PF and LR displays on the CDU, a moving map was displayed, mimicking the CDU's functionality. The CDU incorporated range rings, where the outer ring was either 20, 40, 60, or 80 nautical miles, and the inner ring was always half of that distance. The scale of the map could be altered by the participant using a mapped button on the HOTAS. Enemy fighters' location and heading was shown on the map as well, giving participants more information about their tactical situation and enabling them to orient themselves properly to the threat.

LCO Recovery (LR) Design

It was theorized that an LR visualization would help pilots recover quicker by giving them an optimal recovery path (e.g., climbing and then reducing wing loading versus simply slowing down). However, flutter flight test data and SME advice from the Air Force SEEK EAGLE Office (AFSEO) and Lockheed Martin (LM) were used to determine that while there may be an optimal LCO recovery path, it is highly dependent on that specific airframe, its loadout, and its structural and fatigue history. Therefore, an optimal recovery path cannot be predicted, and specific recovery advice may turn out to be incorrect. Based on the data and recommendations from the technical SMEs at LM and AFSEO, it was decided that the display should simply instruct the pilot to exit LCO by reducing the aircraft airspeed and/or Mach number.

The LR feedback display was designed to help a pilot understand when they were in a suboptimal state and to aid recovery. This display would appear above the PF display if a participant was in one of three conditions: passed the download limits based on their currently selected munition, if the pilot was in LCO, or outside of the flight envelope (out of bounds). The LR design featured two decision aid options: Status and Command

banners as shown in Figure 5. During the experiment, participants experienced either a Status or Command banner. However, during the experimental debrief, the participant was shown each option and asked to rank order them.

The Command and Status displays conveyed the same information to the pilot but differed in their presentation. Status banners told the participant they were either passed the download limits or outside the flight envelope, while command banners commanded the participant to slow down to a certain speed. A participant was only exposed to either a command LR display or a status LR display throughout each scenario. At the end of the experiment, the participant was shown other options of LR displays, status and command, and asked to rank order them.

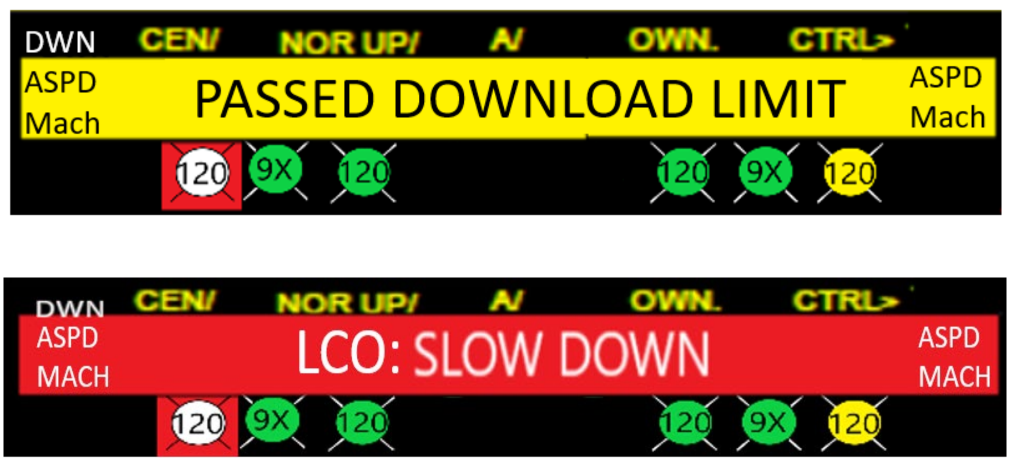

Figure 5: Display with the passed download limit Status banner on the top, and the out of bounds and LCO Command banner on the bottom. Highlighted munitions are those that are not safe to employ in the current conditions, like the one bordered in red (currently selected munition) and one is highlighted in yellow.

Experimental Method

The combination of PF and LR displays create the LCO Support system. The goal of the experiment is to measure the efficacy of this system to increase a participant's SA of their aircraft's conditions and state, and to understand how the displays' presence or absence affects a participant's performance. It is hypothesized that displaying the envelope limits should result in fewer violations of the flight envelope than forcing the pilot to remember them, and if the envelope is violated, participants will spend less time out of bounds. It is also hypothesized that displaying the envelope limits will enhance a participant's SA of their overall aircraft condition and state. Of the possible LCO Recovery display options, it is hypothesized that a status display should be more effective than a command display.

Participants

This research is relevant to the entire population of F-16 pilots, both USAF and FMS. The participant pool was comprised of two groups, including experienced F-16C pilots, and individuals with flight experience in aircraft other than a F-16C. The five F-16C pilots had an average of 1950 flight hours in the F-16C and 260.6 combat hours. Four participants were non-F-16C pilots, two of those having an average of 1160 hours in the F-15C and F-15E, respectively. The last two had general flight experience. Participation was voluntary. All participants were males, between the ages of 27 and 63. To avoid compromising the study, participants were asked not to share the details of the study with others until the end of the data collection period. The participants were volunteers and were available for up to two hours of time.

Scenario Design

The experimental design was a three-by-two-by-two, mixed-subjects, experimental design including the within-subjects variables of LCO Support (off or active), and the Scenario (1, 2, or 3), and the between-subjects variable of the Display Type (Status or Command). The Display Type was randomly assigned. The participants were tasked to fly a flight simulator and achieve air superiority against several Sukhoi Su-27 aggressors in scenarios derived from real training missions. Their secondary task was to stay within the flight envelope. A weapons loadout was chosen that had dynamic flight envelope limits based on external stores and was susceptible to LCO during weapons deployment. Participants had access to written envelope limits verbatim from the TO during every scenario, whether LCO Support was active or not. The flight envelope limits were copied onto a piece of paper folded in half and taped to the bottom of the CDU, or wherever the participant preferred. This information was intended to mimic a kneeboard that pilots use containing pertinent flight information for that day.

The loadout for all experimental conditions included 4 AIM-120 Advanced Medium-Range Air-to-Air Missiles (AMRAAMs) radar missiles and 2 AIM-9X heat-seeking missiles as seen in Figure 4 above. The scenario encouraged the pilots to launch the longer ranged AAMRAMs early in the engagement, producing the largest changes in their flight envelope, such that the pilots grappled with their dynamic limits for the entirety of the scenario. The AIM-9Xs had a simulated range of about 10 nautical miles (nm), and the AMRAAMs had a range of 40 nm. Participants were told that the AIM-120s on their wingtips were the superior missiles and were to be used first. While this is not operationally representative, as pilots can use the Missile Step button to maintain a

symmetrical loadout. However, the standard approach would have imposed fewer changes in the flight envelope, reducing the need for the display concepts under test in the current experiment. Due to the unreliable Missile Step button, which will be discussed later in the Limitations section, the ability to step missiles was not allowed. At the beginning of each scenario, the participant was asked to select the AIM-120 on station 1, and to not step between AIM-120 stations during the scenario. As each scenario unfolded, participants would find they had tighter and tighter restrictions after employing munitions but still had to remain combat effective.

Scenarios were designed to force participants into ever increasingly difficult starting positions, requiring quicker and quicker actions to complete the mission objectives, while having to maintain their flight envelope. The scenario consisted of two to three enemy Sukhoi Su-27 aircraft. Three different scenarios were run, each time flying the control case with LCO Support inactive, and then flying the scenario with it active. The starting distances, altitudes, speeds, and number of enemies were varied within each scenario, but participants were always started at speeds close to their first download envelope limit. Each scenario consisted of the participant needing to eliminate enemy fighters and then intercept new enemies that have moved into the target area. Enemies were spread out so that one was at least 15 nm behind the other so they would approach one by one. Each scenario also moved the participant's starting position closer to the enemies, forcing them to react faster each time. The initial scenario began at 45 nm, the second at 30 nm, and third at 15 nm. Later scenarios had increased enemy skill, starting from "Rookie", and increased to "Veteran". The option "Ace" was not used.

In DCS, several variables were removed from the experiment through the Mission Editor. Invincibility, infinite fuel, and enemy labels were turned on. Invincibility was used so that if a pilot made a mistake and got shot by a missile, the scenario would not end immediately. It did come at a cost to the participant, however, and they were trained that while each successful kill was 100 points, getting hit with an enemy missile subtracted 50 points. Their overall scenario scores were collected to understand their performance, as well as used during data analysis to split the participant population into High Performers and Low Performers.

The researcher expected the participants' performance to increase during scenarios with LCO Support active. It was anticipated that the reduction in the need to cross-reference the aircraft's state with the flight envelope would free up time to maneuver the aircraft, engage in combat, and ease the burden of flying within the flight envelope. It was also anticipated that participants may ignore the feedback warnings to achieve a kill, prioritizing staying alive ahead of overstressing the aircraft. Participants were also told in advance that the scenarios would be stopped mid-flight so that they could be asked questions about what they observed.

Experimental Apparatus and Equipment

DCS 2.5.6 was used to create the scenario, environment and HUD of the F-16C Block 50, and Unity 2019.1.5f was used to create the new experimental interfaces and simulate the HDD CDU visualization. The experiment was focused on the CDU interface, and so the CDU visualization was created with Unity and tied into DCS's export data, but the F-16 HUD was not altered.

The equipment used in this experiment included a Thrustmaster Hands on Throttle and Stick (HOTAS) Cougar, with the optional rudder not used. An LG 65” TV was placed on a 32” high table to display DCS. The CDU was displayed on a ViewSonic VG2455-2k 24” Monitor, using the apparatus from Justin Marsh’s experiment (Marsh, 2019). An HP Z240 desktop was used to run both DCS and Unity. TacView 1.8.4 was used to record the flight tracks in the background for data analysis. The participant was seated 29 inches away from the CDU, mimicking the viewing angle present in the F-16C, without needing to recline the chair. The participant could adjust the height of the chair for comfort with the HOTAS, but most participants chose to keep it at the default height. The user only used the HOTAS Cougar for the experiment and was not required or needed to manipulate any cockpit buttons.

Figure 6: Experimental Setup.

DCS was displayed on the TV and the CDU was displayed through the Unity Editor on the monitor. The HOTAS were affixed next to the participant on filing cabinets

using Velcro strips, achieving as close to normal HOTAS position as possible. Lastly, the view in DCS was zoomed and adjusted at the beginning of each scenario to so that the participant could read the numbers displayed on the MFDs.

Due to the unidirectional flow of the data from DCS to Unity as shown in Figure 7, coupled with the F-16C Block 50 digital model still being in Early Access at the time of this research, some data about the aircraft could not be exported. The information important to this research included the active Master Mode and the selected weapon station. To compensate, the F-16C's weapon switching logic was recreated in Unity. However, several changes were necessary to ensure the Unity program was synchronized with DCS. The largest change was that using the Missile Step button on the stick was not allowed as its normal two operations (short press to change to a similar type of missile on another weapon station, long press to change to a different type of missile) could be seen by one program and not the other, leaving one out of sync. This was an unfixable condition and if it occurred, the scenario would have to be reset and the data would be unusable. In addition, the F-16C's Stores Management System chooses the most inboard missiles to select first by default, which had to be added to the CDU as well. To compensate, at the beginning of each scenario the researcher paused DCS and manually stepped missiles to station 1, the wingtip, and then the participants were asked not to step the missiles from there on. The paddle switch on the throttle, normally used to cancel the autopilot, was mapped to the zoom function of the CDU.

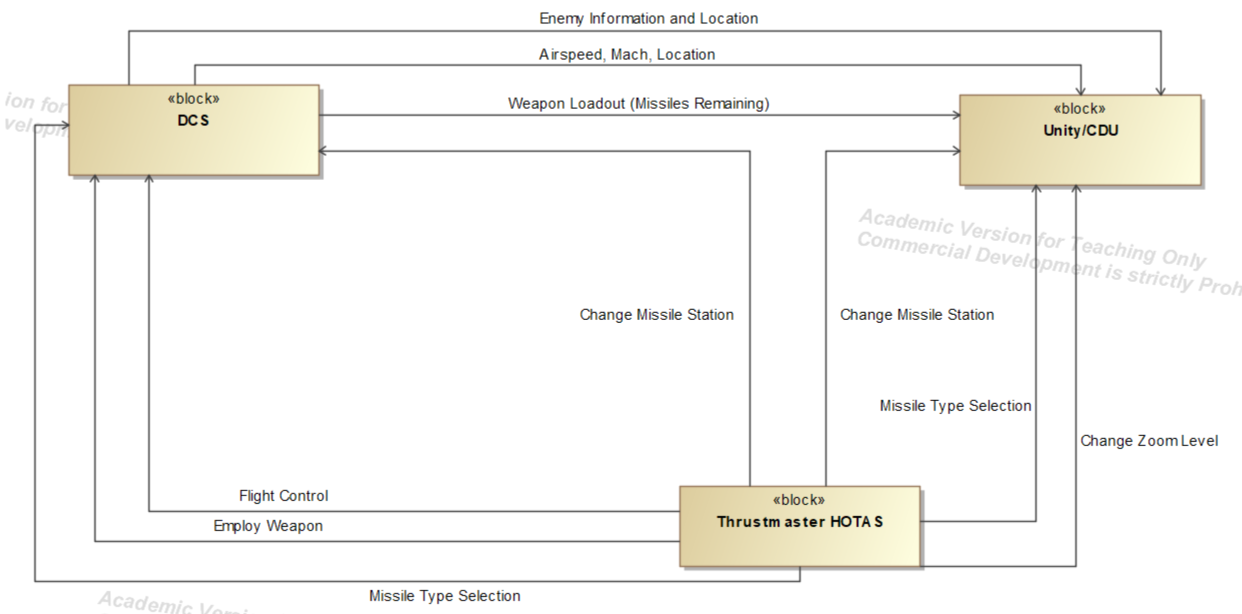

Figure 7: Internal Block Diagram showing the one-directional data flows from each entity. Not shown was the logic inside of Unity used to display the proper TO limits based on the weapon selected and the airspeed and Mach number.

The F-15C/E has its Radar Cursor in a different location on the throttle than the F-16C, instead requiring the use of the index finger rather than the thumb. Originally, the thumb cursor control on the HOTAS was not recognized by DCS, and a different control on the HOTAS was mapped to the radar cursor control using the index finger. Two of the retired F-16 pilots were run through the experiment in this configuration and they found the added task saturation of relearning to use the HOTAS made it nearly impossible to both use the radar and abide by the envelope limits, resulting in poor performance and SA in their trials. Eventually the HOTAS settings were fixed and the thumb cursor control was restored, and the two participants were rerun through the scenarios. To avoid penalizing the F-15 pilots or artificially task saturating them by requiring them to use a different finger than they train with, the index finger control was left active, allowing

participants to use either control according to their preference. This created an equal level of difficulty for all participants regardless of their flight and HOTAS experience.

Procedure

After reviewing the informed consent form, participants were briefed before starting the experiment about each section of the simulation and pertinent participant demographics were collected. The phenomenon of LCO was explained in detail to the participants, along with its consequences for flight as previously discussed. All participants were administered brief training and familiarization scenarios to accommodate them to the simulation environment, and any updates to the normal HOTAS controls they needed to know for the experiment. They were then run through a training session using the current F-16 displays to get comfortable employing missiles using the F-16C Fire Control Radar (FCR), and then one training session also using the experimental interfaces. Each training scenario consisted of a 45 nm starting separation from the enemies to allow the participant to practice lining up a shot. The number of scenarios required varied by participant, with some requiring more than 2 flights to get comfortable using the FCR while flying the aircraft. Participants were encouraged to retry the training scenario until they felt comfortable.

Each participant ran through the same scenarios, first flying the scenario without LCO Support, and then after resetting the scenario, LCO Support was activated and it was rerun. To avoid over rehearsal, each scenario was only run twice: the scenarios did not have as much necessary variability between them required to vary the Display Type shown and maintain task saturation and difficulty. Therefore, only a Status or Command display was shown to a participant, not both.

Because of the dynamic flight envelope, a participant could foreseeably violate the flight envelope at different times during the experiment for different reasons. To accurately capture the SA of the participant, the SAGAT method was used and each scenario was paused during high points of stress to ask the mid-scenario questionnaire. When the scenario was paused, participants were asked to close their eyes to avoid referencing the values displayed on the screen, which could not easily be blacked out. The questionnaire was not always asked at the same time due to the open-ended nature of the scenario. The researcher monitored the visual stress of the participant and paused the scenario when they were focused on trying to fire a missile, evading an enemy missile, or waiting for a missile's radar to go active on its own once employed. Simply asking a post-scenario questionnaire would not have sufficed as it has been shown that after the fact recall tends to contain generalized, simplified content that may not be an accurate assessment (Endsley, 2000). It is possible the mid-scenario questionnaire may not have accurately captured the participant's overall SA when the questions were asked, due to the task-saturated participant focusing on other aspects of the scenario at that moment, or in some cases, on the precipice of starting their crosscheck.

Each scenario ended once all enemy aircraft were defeated, or in some cases, if the participant lost control of the combat situation and was unable to recover and defeat the enemies due to difficulties with the FCR, the HOTAS, or unfamiliarity with the simulator. Once the six trials were complete, a post-experiment questionnaire was used to gather feedback on the efficacy of the LCO Support system, as well as any suggestions. The HUD designs were shown at this time as well, and feedback was solicited.

Questionnaire Development

Not all questions were asked for each scenario, such as the questions pertaining to the LR display if LCO Support was off (control scenario) for that trial. The goal of the first questionnaire was to measure the participants' SA to help understand the participant's actions. The questionnaire was developed such that questions would be asked first that required Level 3 or 2 SA, and then afterwards Level 1 SA questions were asked. This method was put in place so that participants could not build on their own responses and create SA for themselves during the questionnaire.

Mid-scenario questionnaire:

1. Are you currently in bounds? Why/why not?
    a. Confidence level on bounds
2. Current flight envelope restrictions
    a. Confidence level on limits
3. How many enemies are remaining?
4. What is the range to nearest target?
5. Aircraft parameters:
    a. Current airspeed
    b. Current Mach
    c. Current altitude
    d. Current weapon selected
    e. What weapons remaining
6. How does your current/future flight envelope affect your next maneuver/engagement?

7. What is your immediate goal right now?
8. How much are you looking at the CDU?
9. LCO Recovery section:
    a. Did a banner pop up?
    b. What did the previous banner say?
    c. Why did it pop up?
    d. What were you required to do to get the banner to go away?
    e. Did you follow its advice and why/why not?

The confidence level was utilized as a secondary gauge to understand the participant's mindset at the time. If a participant responded with an incorrect answer but a high confidence level, it shows the true state of how degraded their SA is, which could lead to decision mistakes. However, if a participant responded with a wrong answer and low confidence, then it shows they are at least aware their SA is low, which is preferable to being overconfident and incorrect.

End survey

1. How clear were the implications of firing your current missile?
2. Were the download and current limits clear?
3. What was your impression of the banner?
4. Did you expect to see the banner when you did see it?
5. How satisfied are you with the flashing of the banner?
6. How often did you find yourself looking at the missile bar?
7. How clear was the current weapon selected?
8. Do you have any suggestions on how to improve this design?

After each question, suggestions were solicited. After the end survey was conducted, the HUD mockups were shown, and participants were asked to identify rank the designs and to discuss their reasons for this ranking.

Measures

The hypotheses were tested by and data was collected through a mid-experiment questionnaire, post-treatment questionnaire, self-reported perceptions, timers, and scenario score. To measure the effectiveness of the Status and Command recovery displays, a timer activated each time the participant was either past the download limits or outside the flight envelope. It also reported what condition the participant was in: LCO, OOB, or past the download limits. This timer plus the telemetry provided from DCS and Tacview allowed the researcher to characterize the participant's performance with and without LCO Support active.

The following section describes the statistical analysis of the collected data. The data processing was conducted using the commercial IBM SPSS Standard Statistics software package. It was expected that participant familiarity with the F-16 would lead to superior performance, but there were no statistically significant results on the sample population from the mixed factor analysis of variance (ANOVA). For analysis, the population was divided into two groups: 5 High Performers (HPs) and 4 Low Performers (LPs). This was based on the sum of their total scenario scores being above or below the mean. The current F-16 and F-15 pilots were classified in the HP group while the general aviation participants fell within the LP group. Surprisingly, two of the retired F-16 pilots were classified in the LP group.

The ANOVA was performed on the data from the 9 participants, then separately on the 5 HP participants who had the highest total scenario score, then lastly once more on the 4 LP participants with the lowest total scenario score. The dependent variables (DVs) included the score within each scenario as well as envelope violations and durations for the LCO and OOB conditions, respectively. SAGAT scores were scaled by multiplying incorrect answers by -1 and correct answers by 1, and a confidence rating was collected for each SAGAT response on a 1 to 5 scale. The independent variables (IVs) were whether LCO Support was active, the Scenario (1, 2, or 3) and the Display Type used (Status or Command).

The number of envelope violations and durations of the non-LCO (OOB) condition were more likely to be larger than those of the LCO condition because of the evolving nature of the scenarios and the configurations responsible for LCO. A participant could only enter LCO when one wingtip missile was employed, but in any other configuration, a participant would be considered OOB if they exceeded the flight envelope. The goal was still to reduce the number of envelope violations and durations in LCO as they are present at the beginning of the combat scenario and decisions made during this time interval affect the rest of the engagement. It is less than ideal to be stuck in LCO while trying to line up a missile shot as the oscillation degrades hand-eye coordination.

Summary

This chapter presented the experiment design for the collection and analysis of empirical data of actual pilots performing simulated combat missions. The methodology

afforded the researcher the opportunity to gain insight into the efficacy of LCO Support, and the impacts it had on a pilot’s performance and SA.

IV. Results

In this section, the results of the 4 main Hypotheses will be examined based on the data analysis conducted. From the ANOVA, there were no significant effects from LCO Support on any variable for the entire population, so the ANOVA was rerun on the HP and LP groups separately to find statistically significant effects.

The average sum score was 588.87 (SD = 503.7), classifying the group as 5 HPs and 4 LPs. The mean score for the HPs was 155.54 (SD = 25.2) and 13.5 (SD = 26.29) for the LP group, but both groups improved in score in later scenarios, as shown below in Figure 8.

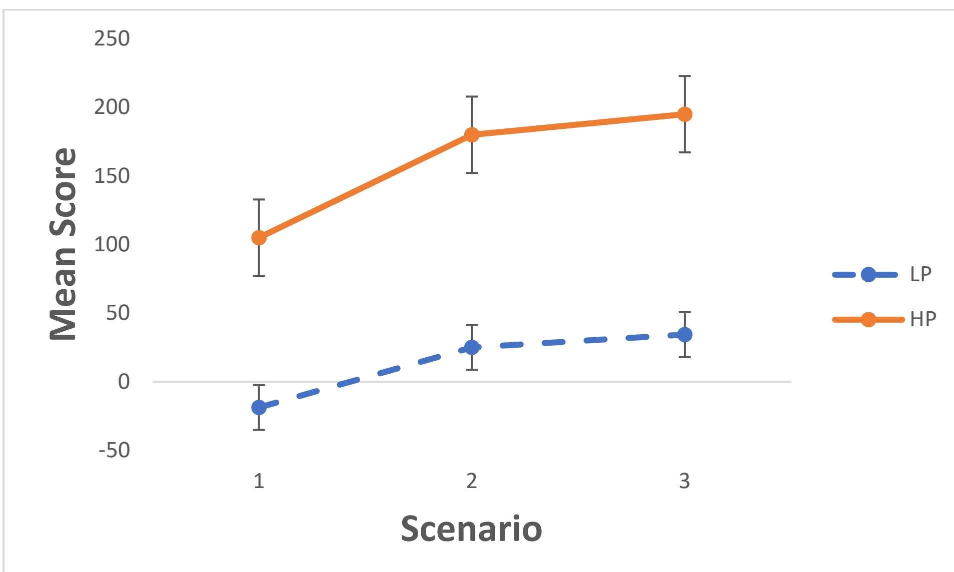

Figure 8: Scenario versus Mean Score based on analysis group. The HPs had a higher score than the LPs in every scenario. Error bars represent the 95% confidence intervals.

LCO Support Results in Less Envelope Violations

H1: Displaying the flight envelope limits have a negative effect on the number of times a participant violates the flight envelope.

It was expected that the number of times that a participant would violate the flight envelope would be lower when LCO Support was present. The DVs of interest in examining this hypothesis were the number of violations in LCO, OOB conditions, and the sum of the two. This hypothesis predicts that providing LCO Support would improve SA, which would reduce the number of flight envelope violations.

High Performers

Neither the LCO Support nor Scenario treatment produced any significant main effects on the DVs for this hypothesis from the ANOVA.

With LCO Support, the mean OOB Violations increased from 1.056 (SD = 0.313) to 1.444 (SD = 0.532), LCO Violations increased from 0.833 (SD = 0.124) to 0.861 (SD = 0.319), and Total Violations increased from 1.889 (SD = 0.313) to 2.306 (SD = 0.811). Although not statistically significant, there was a constant trend of increasing DV values when LCO Support was active. However, to say that more violations occur when LCO Support is active is not supported by the statistics. As seen from the graphs in Figure 9, participants reduced the mean of each of the DVs of this hypothesis in Scenario 3. This can be attributed both to increased skill and comfort with the displays, as well as the reduced number of enemies than the other scenarios.

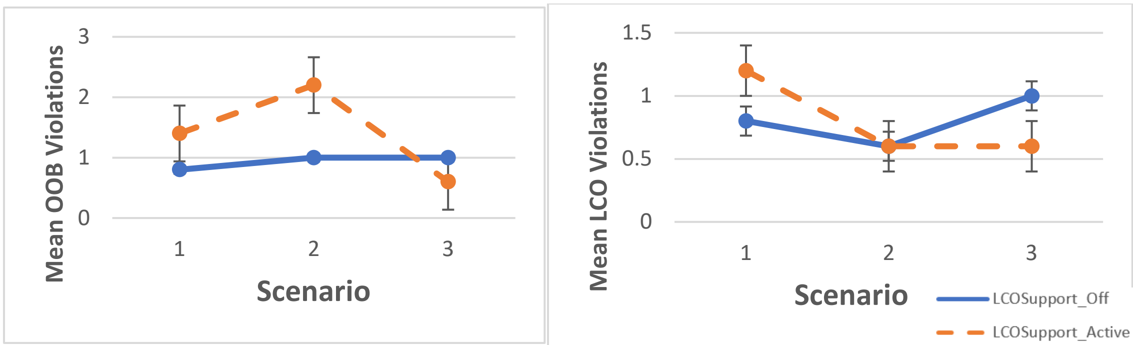

Figure 9: Scenario versus mean OOB violations and Scenario versus mean LCO violations, HP group. Scenario 3 generally produced superior results than the previous scenarios. Error bars represent the 95% confidence intervals.

As the experiment progressed, participants had lower means for each DV, showing that each participant's skill improved even as the difficulty increased. However, LCO Support cannot be attributed to that learning.

Low Performers

Using the 4 pilots with a total Scenario score below the mean, hypothesis 1 was tested again. The repeated measures ANOVA found the LCO Support treatment produced one significant main effect: the number of LCO violations significantly increased from a mean of 0.625 (*SD* = 0.093) to 1.0 (*SD* = 0.118) (F (1, 2) = 81, MSE = 0.01, p = 0.012, η_p^2 = 0.976), against the predictions of the hypothesis. The Scenario treatment did not produce any significant main effects. In Figure 10 below, it seems the LPs made improvements in Scenario 2, having already run two trials in Scenario 1, but when it came to Scenario 3 the difficulty may have increased too much and overrode the skill of the pilots, requiring them to prioritize staying alive rather than avoiding LCO.

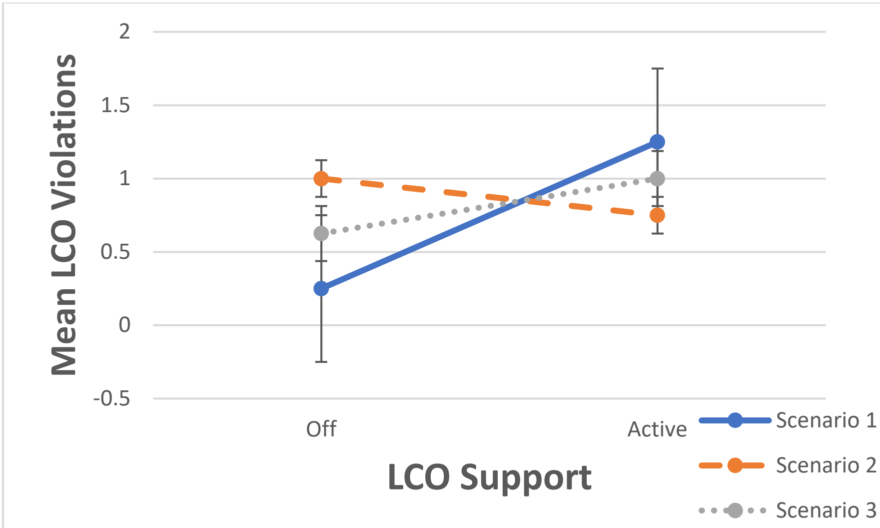

Figure 10: LCO Support vs mean LCO violations, LP group. Only Scenario 2 showed a decrease with active LCO Support. Error bars represent the 95% confidence intervals.

Overall Results

With LCO Support activated, a decrease in the number of LCO, OOB and total violations was expected but not present in the results for any of the group of participants. In fact, LCO Support seemed to increase every DV for each group, against the predictions of the hypothesis. However, the lack of statistically significant results for the HP group signifies that the treatments cannot be expressly tied to the results, and that other factors, such as increasing scenario difficulty or the learning that occurred with repetition of the scenarios also could have played a role.

LCO Support Results in Less Time Spent Outside the Flight Envelope

<u>H2: Displaying the flight envelope limits will have a negative effect on the time spent either in LCO or outside of the flight envelope.</u>

The hypothesis predicted a negative correlation between active LCO Support and how long a participant spent in an OOB or LCO condition. The dependent variables for

this hypothesis were the time spent passed the download envelope limits (PD Time), time spent in LCO (LCO Time), time spent out of the flight envelope in a non-LCO configuration (OOB Time), and the sum of LCO Time and OOB Time (Total Time OOB). A lower time in either LCO or OOB with active LCO Support indicated a high level of SA and acknowledgement of the undesirable aircraft condition. However, it could also mean that a pilot entered a dogfight with the enemy and was never able to recover due to the high starting speeds during the scenario. The mean number of missiles employed in a scenario that did not hit their target (Shots Missed) was also a dependent variable, but more a factor of performance than situation awareness, as a high number of Shots Missed indicates proficiency in lining up shots but also a lack of understanding of the enemy pilot's evasion capability or position. Also included as performance factors in this hypothesis was the Scenario Score and if a participant finished the scenario or not (Finished Scenario).

The first trial of each scenario (Scenario_1) was the control condition with the LCO Support displays inactive, and the second trial of the scenario (Scenario_2) was the experimental condition.

High Performers

From the ANOVA, LCO Support had a significant main effect with a large effect size on decreasing the time spent in LCO (LCO Time), decreasing its mean by 8.21 (*SD* = 1.93) seconds (F (1, 3) = 18.071, MSE = 26.84, p = 0.024, η_p^2 = 0.858), as the hypothesis predicted.

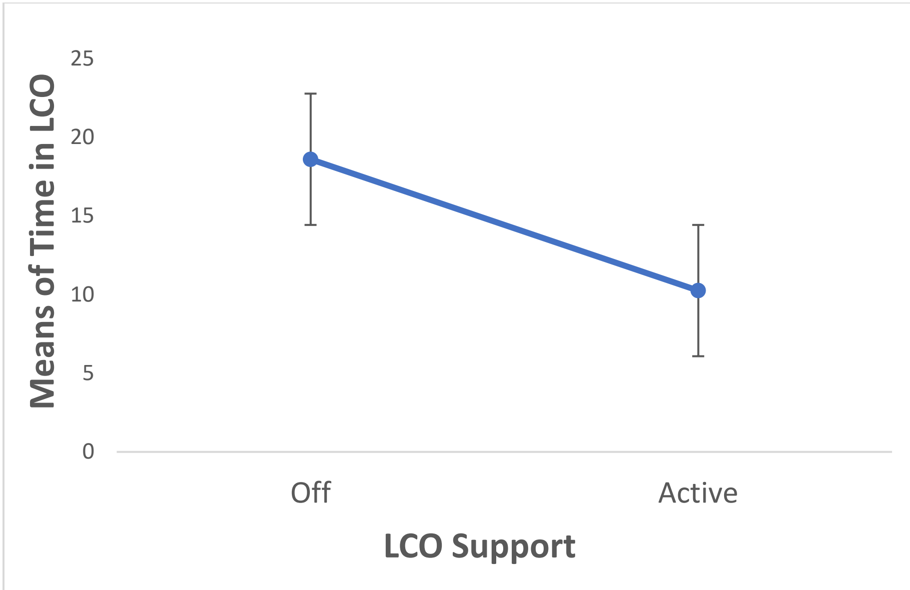

Figure 11. LCO Support versus time spent in LCO, HP group. This shows the decrease in the mean of LCO time when LCO Support was activated. Error bars represent the 95% confidence intervals.

The pairwise comparisons from the ANOVA in Table 1 below highlighted three main differences, but none were statistically significant. First, the mean time spent OOB increased with LCO Support by 2.68 (*SD* = 4.07) seconds ($p = 0.557$). Second, the mean sum time OOB decreased with LCO Support by 5.53 (*SD* = 3.2) seconds ($p = 0.183$). Lastly, using LCO Support affected the following performance variable means: Score decreased by 19.4 (*SD* = 49.8) points, and shots missed decreased by 0.056 (*SD* = 0.336).

Table 1: Pairwise comparisons of the performance variables for the HP group, showing the statistically insignificant results that some variables improved while others decreased with active LCO Support. The "1" case was when LCO Support was off, and "2" was when LCO Support was active.

Pairwise Comparisons

Measure	(I) LCOSupport	(J) LCOSupport	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Finished	1	2	.056	.190	.789	-.548	.659
	2	1	-.056	.190	.789	-.659	.548
Shots_missed	1	2	.056	.336	.879	-1.015	1.126
	2	1	-.056	.336	.879	-1.126	1.015
PDTime	1	2	-20.996	15.976	.280	-71.837	29.846
	2	1	20.996	15.976	.280	-29.846	71.837
LCOTime	1	2	8.208*	1.931	.024	2.063	14.352
	2	1	-8.208*	1.931	.024	-14.352	-2.063
OOBTime	1	2	-2.680	4.071	.557	-15.634	10.275
	2	1	2.680	4.071	.557	-10.275	15.634
TotalTimeOOB	1	2	5.528	3.207	.183	-4.679	15.734
	2	1	-5.528	3.207	.183	-15.734	4.679
Score	1	2	19.444	49.820	.722	-139.104	177.993
	2	1	-19.444	49.820	.722	-177.993	139.104

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Low Performers

From the ANOVA, the LP group's mean time spent in LCO was significantly increased by 17.161 (*SD* = 2.77) seconds with active LCO Support (F (1, 2) = 38.68, MSE = 45.68, p = 0.025, η_p^2 = 0.951). This was contrary to the hypothesis, where a reduction in the duration was expected. There were no significant effects by the Scenario treatment, or the interaction between the treatments. No other variables had significant changes, and every time variable's mean increased when LCO Support was active.

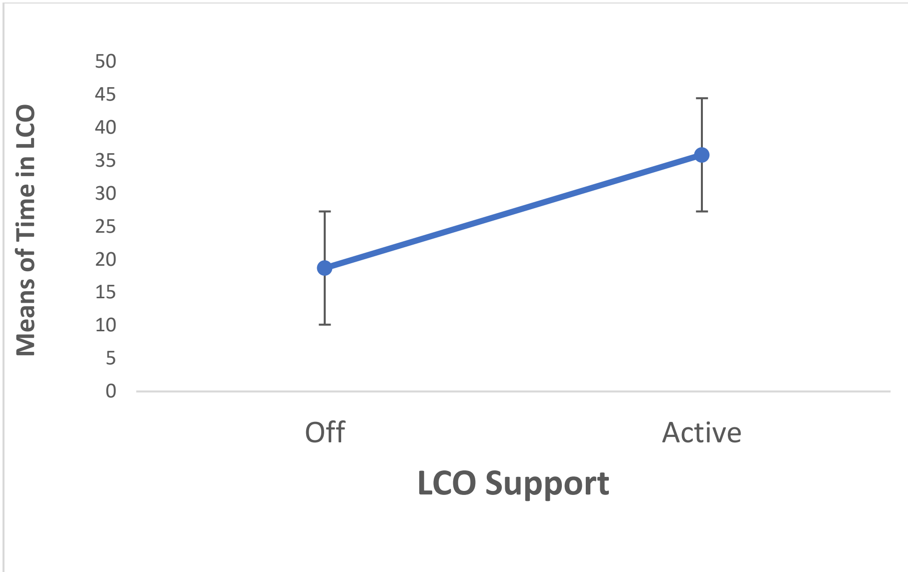

Figure 12: LCO Support versus time spent in LCO, LP group. The mean time in LCO significantly increased with active LCO Support, against the predictions of the hypothesis. Error bars represent the 95% confidence intervals.

Lastly, the LP's mean score increased with active LCO Support, as well as the rate of participants finishing the scenarios and number of shots missed, as shown in Table 2 below. These were all statistically insignificant. This could be attributed to LCO Support but is more likely due to more experience with each scenario, already having one trial under their belt.

Table 2: Pairwise comparisons of the performance variables for the LP group, showing the statistically insignificant results that some variables improved while others decreased with active LCO Support. The "1" case was when LCO Support was off, and "2" was when LCO Support was active.

Pairwise Comparisons

Measure	(I) LCOSupport	(J) LCOSupport	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
Score	1	2	-118.750	90.451	.320	-507.930	270.430
	2	1	118.750	90.451	.320	-270.430	507.930
Finished	1	2	-.292	.336	.477	-1.737	1.154
	2	1	.292	.336	.477	-1.154	1.737
Shots_missed	1	2	-.042	.208	.860	-.938	.855
	2	1	.042	.208	.860	-.855	.938
PDTime	1	2	-20.445	14.910	.304	-84.596	43.705
	2	1	20.445	14.910	.304	-43.705	84.596
LCOTime	1	2	-17.161*	2.759	.025	-29.033	-5.289
	2	1	17.161*	2.759	.025	5.289	29.033
OOBTime	1	2	-23.226	39.657	.617	-193.857	147.405
	2	1	23.226	39.657	.617	-147.405	193.857
TotalTimeOOB	1	2	-40.387	36.982	.389	-199.509	118.734
	2	1	40.387	36.982	.389	-118.734	199.509

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

Overall Results

Due to the dynamic scenarios, not very many interactions were statistically significant and Hypothesis 2's results are somewhat inconclusive but mostly do not support the prediction as most time variables suffered with active LCO Support. In the HP group, LCO Support significantly decreased the time spent in LCO, which conversely was significantly increased in the LP group. This result means that the LPs were possibly on the verge of, or already task saturated. It is possible that adding LCO Support may have increased their workload, resulting in decreased SA. For the HPs who could cope with the task level, the LCO Support aided their SA.

LCO Support Enhances Situation Awareness

H3: Displaying the flight envelope limits will have a positive effect on a participant's SA of their aircraft's conditions within the flight envelope, as well as positively affect their SA of inflight parameters.

The hypothesis predicted a negative correlation between active LCO Support and the incorrect number of SAGAT mid-scenario questions. The dependent variables were the level 2 SA questions of whether the participant thought they were in bounds (Inbounds), their current flight limits (Envelope Limits), and the scaled confidence levels in both. For Inbounds and Envelope Limits, a correct answer was assigned a 1 and an incorrect answer was assigned a 0. The confidence level in an answer was collected on a 1 to 5 Likert scale with 5 being high, and correct answers were multiplied by +1 and incorrect by -1 to achieve a scaled result.

The results of the SA questions are shown below in Table 3. The HP group's mean and confidence levels increased with active LCO Support, in support of the hypothesis. However, for the LP group correct answers to the SAGAT questions all decreased when LCO Support was active, which is counter to Hypothesis 3.

Table 3. SA variable means, confidence levels, and standard errors for both groups. Questions were scored as a 1 if correct and 0 if incorrect. Confidence levels were scored on a Likert scale, and if incorrect multiplied by -1. The HP group's SA and confidence levels increased with active LCO Support, while the LP group's SA and confidence decreased.

Measure: LCO Support	Group	Status	Mean	Std. Error	Confidence Level	Std. Error
Inbounds	HP	Off	0.889	0.143	3.778	1.368
		Active	1	0	4.806	0.095
Inbounds	LP	Off	0.833	0.118	3.333	0.825
		Active	0.75	0.083	2.5	0.85
Envelope Limits	HP	Off	0.833	0.124	3.333	0.87
		Active	1	0	4.903	0.078
Envelope Limits	LP	Off	0.583	0.3	1.75	2.063
		Active	0.5	0.264	0.958	2.084

Questions were asked about the LR display and the participant's flight conditions (Flight Questions Wrong), such as airspeed, altitude, Mach, number of enemies, and more. The flight questions were scored as incorrect if the answer was more than 20% away from the correct answer. A lower number of incorrect answers indicated a high situation awareness of a participant's real-time conditions and consequences for their actions. The results are shown below in Table 4. The HP grou*p* also outperformed the LP group, and while there was a slight increase in the mean of the number of incorrect flight questions when LCO Support was active, the HP group still had superior results than the LP group.

Table 4. Means and standard error of incorrect SA questions for both groups. A lower mean indicates higher SA. The HP group outperformed the LP group, getting less questions wrong about the LR display and the SAGAT questions about their flight conditions.

Measure: LCO Support	Group	Status	Mean	Std. Error
LR Banner Questions Wrong	HP	Active	0.986	0.26
LR Banner Questions Wrong	LP	Active	1.417	0.417
Flight Questions Wrong	HP	Off	0.917	0.334
		Active	1	0.176
Flight Questions Wrong	LP	Off	2.25	1.193
		Active	1.917	0.534

The detriment in SA in the LP group may be due to multiple causes, but from the researcher's observations, the LP participants were so focused on trying to evade and work the FCR that they either did not use the CDU or did not focus on their envelope limits. It was predicted that LCO Support would provide increased SA, but the difficulty of the scenarios may have consumed the participant's attention to the point that they did not use the CDU.

As Hypothesis 3 predicted, the SA of the participants in the HP group increased with the presence of LCO Support. However, the LP group's SA seemed to be inhibited by LCO Support. This shows the ability of the high performing group to comprehend large amounts of data while task saturated. It is unfortunate that the LPs were not aided more, but perhaps scenarios with less difficulty may have allowed them to increase their

SA. LPs were not skilled enough to use CDU to their advantage as much as HPs, which led to decreases or negligible changes in SA.

Status display is more effective than a Command display

H4: A Status display will positively affect SA more than a Command display will.

The hypothesis predicted a negative correlation between the use of the Status LR display and the number of questions missed about the LR display. In the previous Hypotheses, the effects and interactions of the Display Type were ignored, but for this Hypothesis, that interaction is important to understand the changes caused by a change in Display Type.

High Performers

From the ANOVA, there were no significant main effects from the interaction of Display Type with either treatment in the HP population. The mean number of incorrect questions about the LR display was higher for the Status display group than in the Command group as seen in Figure 13, against the predictions of the hypothesis.

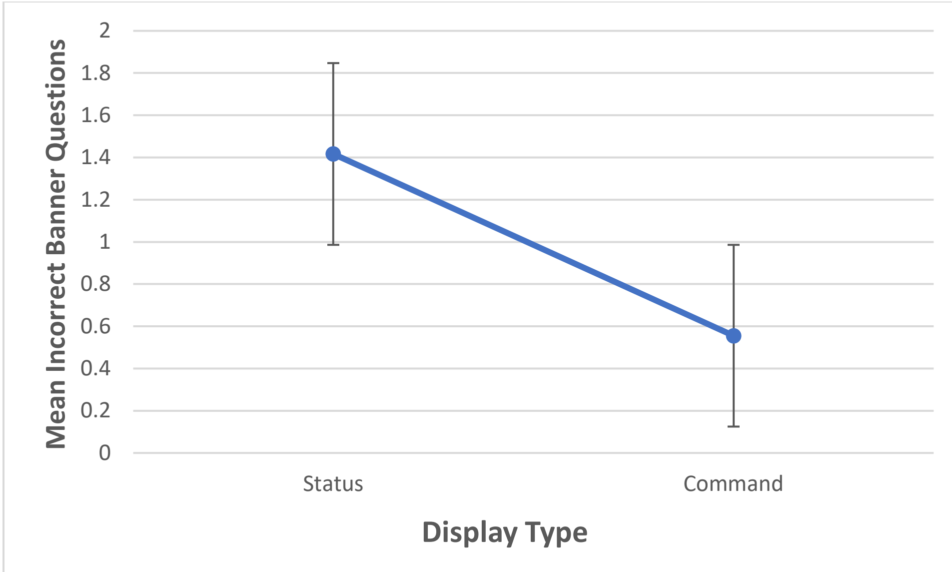

Figure 13: Display type versus mean Incorrect banner questions, HP group. Against the predictions of the hypothesis, the Command display group got fewer questions wrong about the content of the LR display. Error bars represent the 95% confidence intervals.

Low Performers

From the ANOVA, there were no significant main effects from the interaction of the LCO Support treatment and Display Type. For the incorrect questions about the LR display, the mean number of incorrect questions was insignificantly higher in the Status group than the Command group against the predictions of the hypothesis, as seen in Figure 14.

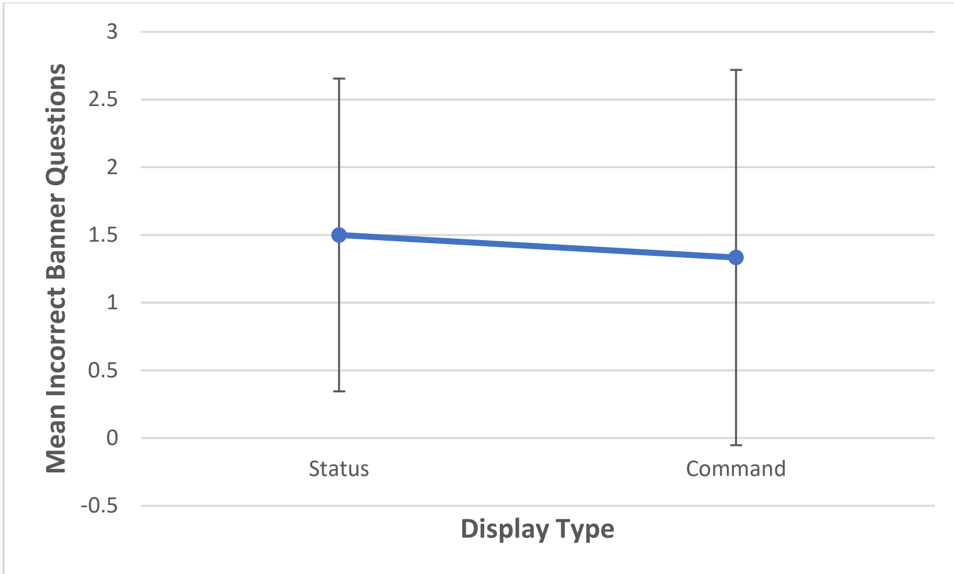

Figure 14: Scenario versus incorrect LR display questions, LP group. Against the hypothesis, the Status display group got more questions wrong than the Command display group, but this is not a statistically significant result. Error bars represent the 95% confidence intervals.

Overall Results:

It was predicted that SA would increase from the presence of the Status display and that it would positively affect performance. The Command display group appeared to have performed slightly better than the Status display group, but this is not supported by the statistics. The random distribution of the Display Type resulted in the HP group having 2 Status and 3 Command display participants while the LP group had 2 Status and 2 Command display participants. On average, the Command display participants outperformed the Status display participants in not only score but also SA questions, which could have contributed to the results in this section.

Of the performance variables, time spent in LCO and OOB are the most telling in this hypothesis, as it may not have been possible to avoid an LCO incursion but if the

participant recognized their mistake quickly due to the decision aid of the LR display, they could limit their time in LCO. Overall, the Command display group outperformed the Status display group by having lower values for these variables, but to say this is a direct result of the Display Type is not supported by statistics.

The SA results are directly related to one single question from the mid-scenario questionnaire: “What did the most recent banner say”? Every participant got that question wrong at least once, some all three times. Most participants could not find the time to read the text but were instead using the color of the banner as truth data whether they were in bounds, past the download limits, or out of bounds/in LCO. Participants reported that seeing a flashing color, along with either memorizing or using the limits present in the corners of the CDU was easier and took up less mental capacity than reading the banner. Some participants got the answer correct in some trials but as the difficulty of the scenarios increased, they no longer had the time to read the banner.

This explanation, coupled with the insignificant results from the analysis, shows that in the LR display’s current form, the performance and SA variables were dependent on the skill of that participant, and that other than the select few statistically significant changes found from the ANOVA, no large differences were present whether a Command or Status display was used.

Post-Experiment Questionnaire Results

As discussed in Chapter 3, the questionnaire asked at the end of the experiment gathered feedback about the experimental design, display design, and asked for any suggestions on how to improve the design. Feedback was recorded on a Likert scale, with 1 being low and 5 being high. Participant’s observations will also be discussed.

Participants felt the implications of firing their currently selected missile were mostly clear ($M = 3.89$, $SD = 1.05$), and that the limits were somewhat clear ($M = 3.56$, $SD = 1.42$). Participants mostly liked the banner ($M = 4.33$, $SD = 1.12$), but on average, did not use the missile bar in the PF display very much ($M = 2.39$, $SD = 1.3$). Participants also felt that the way their currently selected weapon was displayed on the missile bar in the PF display was usable, but not always easy to understand ($M = 3.44$, $SD = 1.33$).

Participants reported liking the intent of the banner, but as mentioned previously, they did not always use it, and usually did not read the text inside the banner unless their task level was very low, and they had time to survey the "cockpit". Some participants reported flying differently in this experiment than they would have in a real scenario, as they were focused on trying to either maximize their score or trying to practice flying tactically at limited speeds.

Participants reported that the flashing banner of the LR display gave them truth data to their position within the flight envelope, something that was not available to them during the scenarios without LCO Support. Without feedback, participants said that it required too much mental energy to stay within the limits and be tactically effective, so the limits were somewhat ignored. With the feedback, however, participants said that it reduced the complex task of checking their conditions to a simple crosscheck to see if a banner was flashing. This was also true for when the participants were unaware of their condition – the banner helped them quickly realize they were in a bad condition when they otherwise thought they were fine. This was a limitation of the experiment in that LCO would not actually occur in DCS, so there was no truth data otherwise. This will be discussed more in Chapter 5.

Some experienced pilots saw this as a good research project, but nothing near ready to integrate in a real mission scenario. This was especially true for the banner displayed when past the download limits, as nothing was wrong at that point, but a large yellow flashing banner was displayed – potentially telling pilots something was wrong.

V. Discussion, Limitations, and Conclusion

Discussion

As seen in Figure 15, although the scenarios were designed to increase in difficulty as the experiment progressed, participants' score generally improved as the experiment went on, with scenario 1's mean score of 44.3 (*SD* = 31.94) increasing to scenario 2's mean of 103.1 (*SD* = 39.43) and scenario 3's of 122.2 (*SD* = 40.08). While the starting distance from the enemies decreased as the scenarios progressed, the final scenario only had 2 enemies rather than 3 to compensate for the close distance. This could account for the higher score as there were fewer threats to evade. More participants finished the later scenarios as well, with mean completion rate increasing from 38% (*SD* = 12%) for scenario 1 to 76% (*SD* = 11%) for scenario 3.

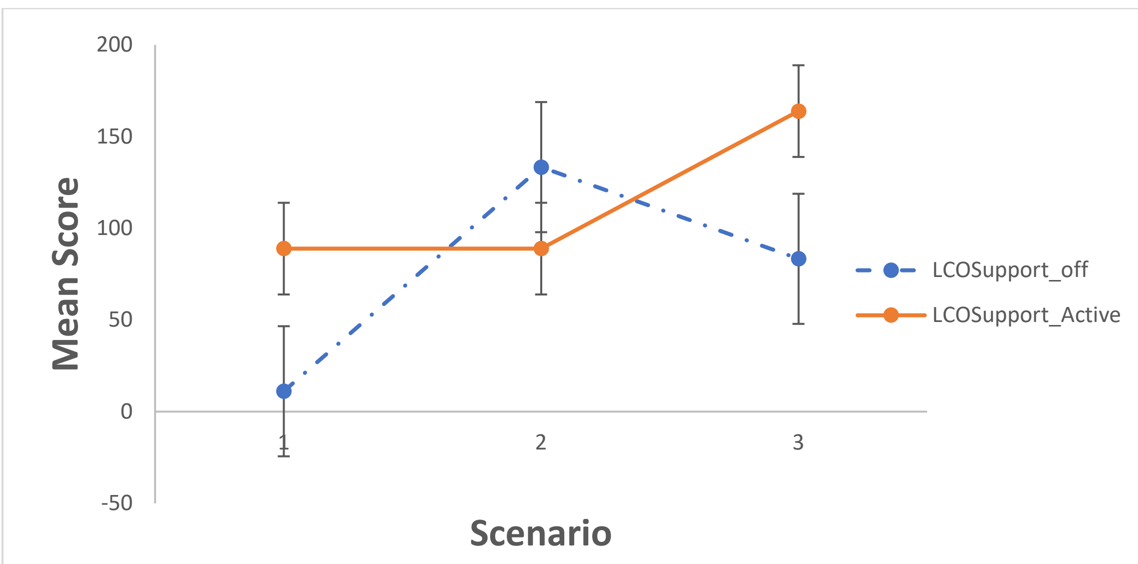

Figure 15: Scenario versus mean Score based on LCO Support, all participants. Overall, participants performed better with LCO Support active, except in Scenario 2. Error bars represent the 95% confidence intervals.

Performance

Overall, against the hypotheses, performance declined with active LCO Support, including the number of envelope violations and the duration of those violations, as well as the Scenario score. The statistics do not support the claim that LCO Support caused a decline in performance, so overall the performance results are inconclusive. Several reasons exist as to why this could be the case, all of which must be discussed: unreliable Fire Control Radar (FCR), Scenario score was prioritized over reducing LCO, not enough training on the new display, and scenario design.

The F-16C Block 50 in DCS displayed some unusual tendencies due to it being an Early Access product, which led to a lot of unpredictability of its FCR. Every participant struggled with using the FCR, because of three common issues: it would not always find the enemies in situations where it should have, DCS would randomly reset the cursor to the middle of the screen when trying to select a target (requiring the participant to re-slew the cursor back to the target), and lastly but most importantly, it was unreliable in holding a target lock. Every participant expressed frustration with how they were initially locked onto a target but randomly the radar would lose lock. This was especially unfortunate when they had fired an AIM-120, were waiting for the missile's radar to go active, and the F-16's radar lock would drop even though the target had not changed course or evaded. This essentially left the missile blind and then forced the participant to reengage and cope with a much closer enemy through no fault of their own. This is a real possibility in a combat scenario, but extremely unlikely when the enemy was not actively trying to obscure their radar cross section and were flying straight and level, as the simulated enemies did. Every participant experienced at least one fault with the FCR, but

not in every scenario. Unfortunately, that data was not collected and cannot be replicated as the effect was not due to any certain circumstances. Increased participant workload due to the FCR issues in an already high workload environment may have decreased the participant's ability to use the SA information on the CDU. The issues with the FCR are a main contributor to poor performance scores, and it is likely participants would have been more successful if the equipment worked as designed.

It is very likely that participants prioritized avoiding enemy missiles and focused on engaging targets more than they put effort towards staying within the flight envelope. One of the most critical weakness of an experiment like this was from the trade between developing scenarios realistic, yet also having participants prioritize flying carefully. It was determined that the experiment should have the participants be at risk of LCO or violating the flight envelope throughout the entire scenario, when in a real combat situation this will mostly likely not be the case. This decision increased the ability to measure the behavior of interest but encouraged the participants to fly beyond the limits, especially as the simulator did not realistically represent the negative consequences of flying beyond the limits.

It is possible that the participants did not receive enough exposure and training on the experimental display before having to use it. Several participants stated that they would need to fly with the new display for about 3 weeks before they would be proficient with it during a combat situation. Each participant flew training flights without the experimental display to familiarize themselves with DCS and could train until they felt they were comfortable, and then once with it on for training before beginning the experiment. It is very likely that the practice did not make the participants skilled enough

to utilize the display under high task saturation levels induced by the scenarios. The simulated F-16C did not fly as expected either – some participants complained it was very unstable in the pitch axis. Certain targeting settings on the FCR were unavailable as well. If a participant chose to employ a missile and turn around to evade rather than continuing towards the enemy, as lower skilled participants did, they tended to have better performance results, contributing to their skill. Some pilots with thousands of hours did not evade after firing a missile, unlike their real tactics. It is unclear why they chose not to perform evasive maneuvers.

It is possible the scenarios were too difficult, and compounded with the FCR issues, participants may have been too task saturated, which compromised their SA. A noticeable dip in performance was seen in Scenario 3, where the participants were started 15 nm from the enemies. The quick reaction times needed to succeed forced the participants to focus more on their survivability than their envelope limits. While this was a realistic training scenario, it did not provide good experimental data about LCO Support. In real life, this may have been an example where a pilot would disregard their limits to survive. The starting distance should not have been closer than 30 nm to allow the pilots to make the conscious decision to enter or avoid LCO, and this would have produced better experimental results.

Each scenario started the participant past the download limit, forcing them to immediately contend with their TO limits. This was done because it was possible that if started too slow, a participant may never put themselves in a position of being susceptible to LCO which would not be a realistic situation and not produce data to analyze.

Situation Awareness

This research employed a mid-scenario questionnaire to assess SA. As predicted, LCO Support increased some participant's mean SA responses compared to the control condition, but this is not supported by the statistics as having a significant effect. Participants provided more correct responses to their condition and position within the flight envelope when LCO Support was active, and participants felt more confident about their responses. The post-experiment questionnaire also found that most participants felt their mental workload was reduced when LCO Support was active, allowing them to focus on the tactical aspects of the simulation.

Overall, the HP group saw an improvement in SA while the LP group saw a decline. This shows the ability of Active Duty pilots to comprehend large amounts of data while task saturated. It is unfortunate that the low performers were not aided more, but perhaps scenarios with less difficulty may have allowed them to increase their SA. Low performers were not skilled enough to use the CDU to their advantage as much as high performers, which led to either small improvements or decreases in SA.

It appeared that the visual attention of participants was focused on the HUD and FCR to target the enemies more than the CDU. Endsley's Information Gap may have been present, where more information was provided to the LP group and they lost understanding due to overload (Endsley & Garland, 2000). This could also be the Perceptual Cycle Model in effect, because the participant's mental model of their aircraft was using much more of the data in DCS than on the CDU, and any changes they made to the flight conditions would likely be more evident in DCS. The inclusion of HUD indicators of LCO may have increased the SA of both groups, as their mental models

would have all the required data to reference in one place and their visual attention would not be as divided.

Decision Aids

This research also employed decision aids to assess SA and how it affected performance. Against the prediction, neither decision aid was particularly influential, with the most likely result being that more skilled participants were in the Command display group because their SA and performance results were slightly better than the Status display group. It was expected that the decision aids would assist the LPs more than the HPs in the experiment, as it was predicted the HP group would be able to effectively complete the scenarios following the envelope guidelines and flying tactically. However, most participants did not recall the text of the decision aid and were more focused on using its colors to guide themselves. This created no discernable difference between either group based on the decision aid treatment. Based on that post-experiment feedback, it seems that the experimental design for the decision aid was not effective enough for either group. This result combined with the inconclusive performance results shows that further design maturation is required.

Feedback on HUD Designs

All participants expressed an affinity for indicators in the HUD about their LCO/OOB status, and some complained about the lack of one during the experiment. Participants stated that the HUD should contain the most pertinent information and implied that LCO/OOB status was among this most pertinent information. Unfortunately, while color proved in the experiment to be effective on the CDU as predicted by McCandless (McCandless et al., 2005), that is not a design option on the HUD so

different techniques were explored to present LCO information. It was expected that each pilot would have different preferences as to how information should be presented on the HUD, so after completing the experiment participants were asked to provide suggestions for this display. Alternate conditions were then discussed. All but one participant expressed that a HUD alert should issue a command instead of a status alert. Some said this could prevent pilots from ignoring the alert, while others said that “pilots like simple commands – monkey see, monkey do”.

For the situation in which the pilot is passed the download envelope limits but not out of bounds or in LCO, participants preferred having an “LCO” indicator next to the Mach number, airspeed indicator, and if present, above to the Dynamic Launch Zone (DLZ) caret as shown in Figure 16. These are areas pilots are frequently watching and although the DLZ is somewhat cluttered already, this is where a pilot’s attention is at when trying to employ a munition. Pilots also liked having a flashing box around the condition (Mach, airspeed, g’s, weapon station, etc.) that is passed the download limit, as this immediately tells them what is at fault instead of them having to crosscheck every value with their restrictions. This could be expanded to include not just LCO restrictions but all flight restrictions to reduce the amount of time necessary for a pilot to recognize the condition that is out of bounds and then rectify it.

Figure 16: Mockup of the Predictive Feedback display in the HUD using a screenshot of the HUD in DCS. LCO markers are present next to the missile selected, airspeed, and DLZ Caret. Flashing boxes are drawn around the Mach and weapon selected.

For the situation in which the pilot is currently experiencing LCO or is out of bounds of the flight envelope, participants preferred having a flashing "LCO" in the middle of the HUD, similar to the "FUEL" warning if the aircraft reaches a certain fuel level. Most participants preferred having the limits that are displayed in the CDU in the HUD as well, in the lower middle of the screen so that they do not need to look outside of the HUD to fully understand the situation.

Figure 17: Mockup LCO Recovery display in the HUD, created using a screenshot of the HUD from DCS. A flashing "LCO" appears in the middle of the screen, similar to a low fuel warning. The limits are also displayed in the lower middle of the screen for easy reference.

One participant suggested that instead of a command to slow down, like the one that was used in the LR display, if a solution is available that would expand their capability, such as to change the missile currently selected ("Step Missile"), then that message should be displayed instead of "Slow Down". This would allow the pilot to avoid LCO and maintain their current aircraft condition if they changed from shooting a wingtip missile to an inboard one. This does not work with all situations or loadouts, as it may be the last of a certain type of missile, or the pilot may want to maintain external symmetry for various reasons. However, this option should be considered to allow the pilot more flexibility in their options while also increasing their SA.

Limitations

As DCS was not modifiable, LCO could not be incorporated into the game. Therefore, without the LCO Support display active, there was no feedback in DCS that the participants could perceive to know they were out of bounds. The screen did not shake, the displays were still readable, and the aircraft did not suffer flight control issues. Participants had no incentive to change their tactics. Many of the long times spent in LCO can be attributed to LCO Support, but also the lack of consequences of being in LCO. Real feedback in DCS might not have reduced the number of violations, but it would provide an update to the participant's mental model of their aircraft and allow them to feel the weight of their decisions, allowing them to learn and change their tactics.

Due to the F-16C Block 50 Early Access model's limitations, not all data was available to export. The two most crucial pieces of data, the currently selected master mode (Air-to-Air or Air-to-Ground) and the currently selected weapon station, were not exportable data items, unlike other models like the F-15C which is fully implemented. To provide participants with an accurate stores management display on the CDU, the weapon select/shoot order was replicated within Unity, and the missile bar concept from Figure 4 was developed to give participants knowledge of which munition was selected. In a simple test flight in DCS with no enemies, the functionality of using the HOTAS to step a missile and having it also register within the Unity program was mostly reliable. However, as soon as DCS had other entities like enemies and missiles to handle, support for the Missile Step button was unreliable and often DCS would recognize the missile step but Unity would not. This led to a case in which Unity and DCS were out of sync,

which caused havoc on the timers and possibly made the CDU display incorrect warnings.

Due to the unreliable Missile Step button, it was not allowed to be used, which limited the participant's options to mitigate the problem of LCO. Participants were instead forced to continually contend with their decreasing dynamic flight envelope limits with no capability to fix them. Almost every participant reported that flying at the speeds the TO limited them to was unreasonable in a real engagement, and that they would most likely not survive at such speeds. They would have much rather changed missiles than slowed down, something that was not possible to perform in this experiment.

Recommendation

The experiment indicated that the presence of LCO Support provided by the proposed system can increase a pilot's SA, especially under high task saturation. However, the inconclusive results on the decision aids, coupled with the decrease in performance across the population and the many limitations on the experiment, demonstrates a need for a higher fidelity experiment with a more realistic flight simulator and HOTAS to obtain true results. For this experiment, expert pilots were used but not expert equipment and therefore the results may change with more reliable equipment. This is also a reason to amend the display design, and to open the location of the LCO Support to screens other than the CDU. It is not clear from this experiment if the top of the CDU is the most effective location for LCO Support – the most optimal location may only be in the HUD, or on the FCR. The design would need to be adapted for these screens as there is less free real estate on the FCR and HUD.

A different scenario in which participants are asked to react to a message on the CDU over and over could have generated clearer results, but that is even less realistic and would omit too many real variables such as fatigue, task saturation, attention patterns (crosschecking), and even simulated workload such that the results may not be usable. Any future scenario that does not incorporate air combat will not be operationally representative because the dynamics of the combat environment place a pilot under a unique task and stress load that is hard to replicate.

It is recommended that future examination of this concept be conducted with the incorporation of actual consequences for flying either in LCO or out of bounds of the flight envelope, such as shaking the screen, blurring the displays, or making flight controls slightly more difficult. Corresponding with this, a high-fidelity simulator should be used that provides reliable avionics and control mechanisms, to reduce the likelihood that an unrealistic error will occur. Also, it is recommended that the HUD designs be incorporated in the experiment to test the complete design, rather than only certain parts as this experiment was limited to.

Lastly, for future examination of this concept, a mechanism that allows the participants to fix their situation through a command prompt or decision aids should be incorporated, and this will allow the researcher to determine the efficacy of different prompts or decision aids through response time and SA measurements.

Summary

There appears to be potential benefits to the use of LCO Support over requiring pilots to memorize their envelope limits in today's F-16C fleet, as well as the potential

for use in other airframes. There is also the potential to expand the concept to include other data to be displayed, such as acceptable g limits, roll rates, and more. The research contained in this paper is limited by time, funding, and manpower, however there is more to be explored and learned in this application with favorable results in the field of human factors considerations for pilots.

Appendix A. Extra Statistics

As an extra measurement to see if participants were looking at the LCO Support display, the amount the participant was using the CDU was asked on a Likert scale. From the ANOVA using a 95% confidence interval, as shown in Figure 18 below, the Using CDU variable was increased significantly from both the LCO Support (F (1, 3) = 35.78, MSE = 0.36, p = 0.009, η_p^2 = 0.923) and Scenario (F (2, 6) = 5.01, MSE = 0.62, p = 0.053, η_p^2 = 0.625) treatments. The mean of Using CDU had a significant change, from 2.139 (SD = 0.319) to 3.33 (SD = 0.278), a 55.6% increase when LCO Support was active (p = 0.009). This affirmed that participants were indeed using the LCO Support display, even if their answers to the SA questions were incorrect.

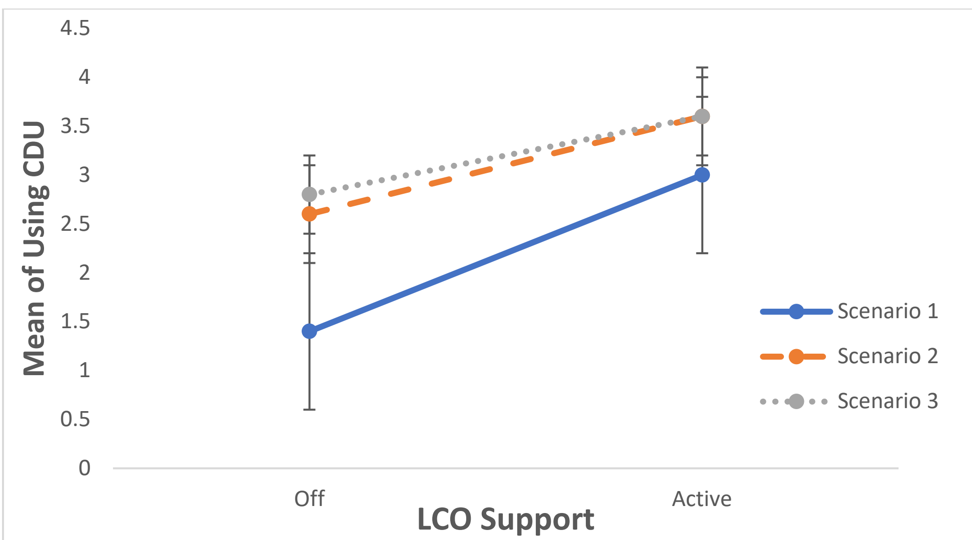

Figure 18: LCO Support versus how much the participant was using the CDU, on a Likert scale from 1 to 5. Participants used the CDU significantly more when LCO Support was active. Error bars represent the 95% confidence intervals.

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14. ABSTRACT
The U.S. Air Force F-16C's flight envelope is defined by its external weapon stores configuration, and the employment of some munitions at certain speeds can cause the F-16 to enter a flutter-like state called Limit Cycle Oscillations (LCO). In LCO, the pilot experiences turbulent vibrations reducing their fine motor control. The current research attempted to help pilots anticipate an LCO-susceptible configuration by projecting the consequences of employing certain munitions. It was hypothesized that the new displays would result in fewer flight envelope violations, fewer LCO occurrences, and increased situation awareness. The results show that there are situation awareness benefits if the pilot is not task overloaded, but the performance results were inconclusive. Further design maturation is necessary to understand the implications of the new display.

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