ABSTRACT

EFFECTS OF COMMUNICATION AND CONTROL LATENCY ON AIR TRAFFIC CONTROLLER ACCEPTANCE OF UNMANNED AIRCRAFT OPERATIONS

By

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Integration of Unmanned Aircraft Systems (UAS) in the National Airspace System will require UAS to meet the standards expected of conventional manned aircraft, including interactions with air traffic controllers (ATCo). To study the effect UAS delays have on ATCo acceptance of UAS operations eight ATCos managed traffic scenarios with conventional manned aircraft and one UAS. To mimic the potential latencies of UAS operations 1.5 or 5 second delays were added to the UAS pilot's verbal and execution initiation responses. Delays were either constant or variable within each scenario. While ATCos were tolerant of UAS delays, the duration and consistency of verbal and execution delays did affect communications and ATCos' experiences managing traffic. Limitations and recommendations for future research are discussed.

EFFECTS OF COMMUNICATION AND CONTROL LATENCY ON AIR TRAFFIC CONTROLLER ACCEPTANCE OF UNMANNED AIRCRAFT OPERATIONS

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CHAPTER 1

INTRODUCTION

Unmanned Aircraft Systems in the National Airspace System

Unmanned Aircraft Systems (UAS) have a variety of practical uses for private and public sectors such as land surveying, disaster response assistance, law enforcement and climate research. For example, in 2006 a General Atomics MQ-9 aircraft flown from NASA Dryden Flight Research Center assisted fire-fighting efforts by providing timely information on the progression of wildfires (Merlin, 2009). Commanders on the ground used this information to more effectively allocate resources and avoid hazardous situations. Their demonstrated usefulness has led to a surge in demand from public and private groups to use unmanned aircraft in the National Airspace System (NAS). However, the procedures allowing UAS assess to the NAS are presently more time consuming and laborious than those for manned aircraft.

Currently, there are two methods that unmanned aircraft may obtain approval from the Federal Aviation Administration (FAA) to operate within the NAS. The first method is that the mission be granted an experimental airworthiness certificate for private sector operations. The second is that a Certificate of Authorization (COA) be obtained for public sector operations. A COA does not grant routine access to fly UAS in public airspace, instead prior coordination with the air traffic management services is required to ensure that the requested operation can be conducted safely, without interrupting airspace efficiency. Neither of these existing processes grants UAS operations routine access into the NAS like manned aircraft. In recognition of this demand to integrate UAS into the NAS, the FAA Modernization and Reform Act of 2012 was passed by the U.S. Congress. This law requires the FAA to develop standards for UAS certification and integration to the NAS by 2015.

At a minimum, “UAS will be required to act and respond as manned aircraft do” (International Civil Aviation Organization [ICAO], 2011, p. 5), in order to gain routine access to the NAS. This requirement not only involves assessing the performance capabilities of the unmanned aircraft, but also the characteristics of the UAS when it is interacting with other aircraft and air traffic management (ATM) services. UAS-ATM interactions include responding to instructions from air traffic controllers (ATCo) and having awareness of nearby aircraft (Shively, Vu, & Buker, 2013). Understanding how manned aircraft currently operate will shape the standards of performance that will be expected of unmanned aircraft. However, the current regulations for manned aircraft can be broadly interpreted and may not be applicable to UAS. For example, FAA regulations do not specify a time limit on communication delays or pilot execution of instructions from ATCos. Instead, the existing guideline only requires that pilots respond promptly to instructions. A UAS pilot remotely located from the aircraft will have different understanding of the state of the aircraft, surrounding traffic and terrain depending on the equipage of the aircraft, pilot interface and level of control, and the communication/datalink architecture. These factors could change the timing of the pilot’s response to controller instructions. Therefore, understanding the interactions between UAS, manned aircraft, and air traffic control services is necessary for establishing standards certifying UAS operations.

Controller-Pilot Communications

In the NAS, pilots and controllers currently interact through radio communications. This is the primary means through which ATCos manage traffic in their sector. To maintain safe separation of air traffic, the ATCo's instructions need to be accurately transmitted to pilots. Due to the high demand for safety, the structure and content of pilot-controller communications has been developed for efficient information transfer (Connell, 1996). Ideally, the communication process includes three parts: the initial call, readback, and hearback. For example, an ATCo would issue an instruction "American 755, turn right, heading 320." Pilots onboard the aircraft would respond, or readback the message "Right, heading 320, American 755." The ATCo actively listens for the pilot's read back of the instruction and monitors that the aircraft has executed the command. This scheme allows pilots and ATCos to collaborate ensuring that information has been correctly transferred and understood (Morrow, Lee, & Rodvold, 1993).

Deviating from established phraseology and readback/hearback procedures contributes to communication problems that can result in incidents and accidents. If the read back is incorrect or the pilots do not respond, the controller must reissue the instruction. Excessive delays in responding to the ATCo's instruction will render it ineffective. When this occurs the controller may re-issue the instruction, issue a new instruction to that aircraft or to another aircraft. Because the communication process is time consuming, it is a bottleneck in the ATCo's workflow, especially when multiple aircraft must be managed within a short period of time (Yang, Rantanen, & Zhang, 2010). An ATCo's job is centered on communications, in preparation or response to communicating with pilots and other ATCos. As such, the amount of time controllers spend communicating with aircraft is an indicator of their workload (Porterfield, 1997). Inefficient communications increase ATCo's workload and can negatively affect their performance.

Howard (2009) described four socio-environmental challenges to pilot-controller communications. First, technical constraints only allow one person to speak at a time on a common radio frequency. The quality of the message is dependent on the power of signal transmission and reception, and headset and microphone quality. For instance, propagation and transmission delays contribute to the occurrence of step-ons (Nadler, DiSario, Mengert, & Sussman, 1992). A step-on occurs when one party on a common frequency begins transmitting a message before another has ended their transmission. Step-ons reduce transmission success as the message is partially or fully blocked, further reducing communication efficiency (Wourms, Ogden, & Metzler 2001). Second, speech is highly regulated to maximize reliable information transfer such that who speaks in turn, the information that is presented and the format of the message are clearly defined. This structure allows information to be relayed efficiently, but pilot and ATCos may not necessarily develop a complete picture of the other's understanding of the situation due to the terse nature of the message (Chiappe, Rorie, Morgan, & Vu, 2014). Third, the cultural organizations of pilots and ATCos are vastly different. The air traffic management promotes a systems-wide approach towards defining success, whereas pilots' culture is more individualistic, emphasizing the goal of the aircraft's destination (Cushing, 1995). Lastly, pilots and controllers operate within their own time- and safety-critical environments. Pilots busy in the cockpit may miss part of an ATCo's message or only read back part of the message. An ATCo that is busy with other aircraft does not always have time to actively listen for a full read back, or may try to reduce communication time by stringing together multiple instructions to several aircraft.

Common issues contributing to communication errors are pilot and controller workload (Howard, 2009), similar sounding call signs (Cardosi, Brent, & Ham 1996), poor microphone technique, accent, rate of speech (Cushing, 1995), and procedural deviations (Morrow, Rodvold, & Lee, 1994). In addition, when ATCos transmit more complex messages, pilots are less likely to provide a complete or accurate read back (Morrow et al., 1994; Prinzo, Hendrix, & Hendrix 2009).

Despite these challenges, the pilot-controller communications are effective. That is, ATCos and pilots have a high rate of success communicating on their first attempt. Cardosi (1993) and Cardosi et al. (1996) analyzed tapes from En Route and Terminal Radar Approach Control (TRACON) to measure the end-to-end time required for controllers and pilots to successfully transmit a message. For the En Route centers they measured four time components of pilot-controller communications, and the percentage of transmission errors. A successful transmission took, on average, 10 seconds (SD = 5.91). The time for the controller's initial instruction averaged 4.85 seconds (SD = 2.30). The time between the controller's instruction and pilot response averaged 3.31 seconds (SD = 4.80). Lastly, the duration of the pilot's correct read back averaged 2.61 seconds (SD = 1.83). The average communication time in the TRACON environment, the airspace associated with a particular airport or group of airports, was less, illustrating that the pilot response latencies will differ depending on the phase of flight. Although these means are informative, it does not provide an indication of the time period that controllers perceive as acceptable for pilot latencies. In fact, the standard deviations for the times indicated above are often greater than the means themselves, reflecting the large variability in times associated with pilot delays. Moreover, these times include delays that should be regarded as unacceptable because 12% of the communications involved ATCos repeating their commands when pilots failed to respond in a timely manner.

To evaluate the effectiveness of the system, Cardosi and colleagues (Cardosi, 1993; Cardosi et al., 1996) examined the transmissions success rate for En Route centers. They found that 84% of transmissions were successful on the first attempt. In TRACON environments, transmissions had a 98% success rate for the first attempt. Although ATCos made additional calls to repeat or clarify their instructions for a small percentage of transmissions, the ATCos were able to maintain proper traffic separation assurance. Thus, both studies show that although the ATCo clearances are not always successfully transmitted on the first attempt the ATCo corrects any communication errors to ensure safety of flight. UAS operations will need to demonstrate a comparable level of communication performance as manned aircraft when interacting with ATCos.

UAS Control and Communication Latency

The unique characteristics of UAS operations introduce several challenges for their integration into the NAS. The pilot's separation from the aircraft introduces technological issues of command, control, and communications (C3). The technological constraints are transferred into operational difficulties for pilots that will also impact their interaction with controllers. The C3 architecture of UAS will introduce delays for pilots communicating with air traffic management services in addition to delays associated with controlling the aircraft. Stansbury, Vyas, & Wilson (2009) described C3 architectures that are commonly used by unmanned aircraft. He grouped different UAS into three categories based on the operational range and endurance of the aircraft. These categories are low, medium and high endurance unmanned aircraft.

One distinguishing characteristic between these categories are the C3 architectures linking the pilot in the control station to the aircraft. Typically, all three types of UAS utilize radio frequency line of sight (RF LOS) when the aircraft is in close proximity to their ground control station. Satellite mediated, or beyond line of sight of radio frequency (BLOS) C3 architectures are used when relaying information across greater distances for medium and high endurance UASs. Latencies emerge when linking information between the control station, aircraft, intermediate satellite, and ATCo. The latencies of BLOS operations are expected to be greater than those of RF LOS which more directly links the control station and aircraft. The use of RF LOS by low endurance UAS would mean relatively short latencies. Medium and high endurance UAS may use both RF LOS and BLOS during operation meaning that the overall latencies will be longer. When a UAS switches between RF LOS and BLOS data link connections transmission latencies will vary. The variability in delays associated with UAS communications may influence ATCo performance since it will be harder for them to predict and accommodate for the delays.

Delays in Controller-Pilot Communications

Delays are known to negatively affect the performance (Rantanen, Esa, McCarley, & Xu, 2004). As an example, in the case of pilot-involved-oscillation (PIO) the frequency of the aircraft's response to the rate of pilot input creates a feedback loop in which compensatory control actions can cause the aircraft to become increasingly unstable. However, with experience, operators develop strategies to diminish the effect of delays. In the case of PIO the common strategy is for the pilot to momentarily take their hands off the controls allowing the aircraft to stabilize before making additional control inputs. In response to new delays, pilots and controllers may adjust their communication style which can contribute to more communication errors (Prinzo et al., 2009).

Using remotely located robotics, Lane et al. (2002) tested various delay durations on operator performance and frustration. Similar to the strategy pilots use when encountering PIO, operators adopted a “wait-and-see” strategy when delays in the robot’s response was greater than 1 second (Lane et al., 2002). The “wait and move” strategy involves inputting a command and verifying that the machine completed the command before giving additional commands. These experiments, however, have used relatively constant delays. In another test from Lane et al., long delays (1–6s) that were not expected by the participants accounted for approximately 2–3% of all delays. The other 97% of delays were less than 300ms. When the longer delays were experienced, participants would assume that the machine was broken and became frustrated. Although the long delays were frustrating, operators reported that the greater issue was variability. These issues parallel the communication architecture in place for some UAS operations. As the UAS switches connections between LOS and BLOS controllers’ expectations of the response latency from pilots will be disturbed as the communication and control latency fluctuates without notice.

Fortunately, as new communication systems have been developed researchers have tested their feasibility in contrast to the systems currently in use. A few of these investigations have focused on communication latency for manned aircraft pilots and

ATCos, and the effect latency has on communications and system performance. Zingale, McAnulty, and Kerns (2003), for example, tested a very high frequency, digital link mode 3 (VDL3) system against a standard analog communication system in a high-fidelity simulation. The VDL3 system had features to prevent step-ons, but also included a 350ms throughput delay. Despite the additional delay, pilots were able to successfully complete more communications with the VDL3 system, and rated it as better than the analog system. However, the effect delays had on controller-pilot communications was likely underestimated as the VLD3 system includes anti-blocking technologies.

Using a similar VDL3 system with participant controllers, Sollenberger, McAnulty, and Kerns (2003) tested 3 levels of ground-to-air delays at 250ms, 350ms, and 750ms, and 3 air-to-ground delays at 260ms, 360ms, and 790ms. The two shortest delay conditions were not different in terms of system performance, ATCo ratings, or communication issues. The longest delay condition (750ms) resulted in an increase of controllers overriding pilot communications. Controllers rated the longest delays as interfering with communication tasks. In addition, fewer optional services were offered by controllers when the longest delays were in place. On average, per call, controllers occupied the voice channel for less time with the longer delay. This could mean that controllers increased their rate of speech, omitted words from their transmissions, or both. Although controllers may adopt strategies for communication delays, increasing their rate of speech, message complexity, or use of non-standard phraseology will only introduce more problems in the communication exchange (Prinzo et al., 2009).

Nadler, and Mengert (1993) compared the effects of communication latencies of various satellite and voice switching equipment on pilot-controller communications.

Using a simulated En Route environment, communication workload was manipulated by the level of traffic managed, and communication latencies mimicked the delays of the current voice system and the expected delays of a satellite system. Communication workload was moderate, high or very high. The communication delay conditions ranged from durations of 225ms to 485ms for controllers and 0ms to 330ms for pilots. The longest delay conditions associated with certain voice switching equipment and satellite mediated transmissions were found to increase step-ons. However, this result was only obtained when the communication workload was very high. Therefore, this simulation likely underestimated the number of stepped-on messages that required additional communications because no realistic blocking feature was included in the voice system.

In two experiments, Rantenen et al. (2004) tested the effects of audio delays between pilots and controllers on controller vectoring performance. The first experiment was a simplified part-task simulation in which controllers were asked to time the transmission of a turn instruction for aircraft intercepting a fixed point away from a runway. The manipulation included the addition of two delays in response to the end of the controller's instruction. The delays were four levels of systematic transmission delay and two levels of pilot response delay. The systematic audio delay was set at 150ms, 250ms, 350ms, or 1000ms. Two levels of pilot delay were used: No Pilot Delay or a variable pilot delay based on a Gaussian distribution with a mean delay of 2 seconds. Controllers' vectoring performance was less accurate when the pilot delay was present. Also, controllers' were found to issue their turn instruction earlier when the pilot delay was included.

The second experiment examined the cumulative effect of delays on controllers' performance separating aircraft. In this test controllers were asked to determine if two intersecting aircraft were at the same altitude, and if so to issue an instruction to one aircraft to descend. Each trial consisted of four communications: controller's request for an aircraft's current altitude, pilot response, controller issuing an altitude instruction, and pilot readback. The same delays (systematic and pilot) were used in the experiment previously mentioned. In general, longer systematic audio delays and the presence of pilot delays decreased the lateral separation of the converging aircraft. In greater detail however, combinations of pilot and audio delays resulted in non-linear outcomes of lateral separation and communication times. Rantenen et al. (2004) found that the effect of additional delays in a communication task not only increases communication times by the combined value of the delays, but also includes additional time for operators to respond to delays.

The communication and command latencies for UAS pilots and experienced by controllers will likely be greater than those investigated by previous research because of the cumulative latency of BLOS operations. Fern, Kenny, Shively, and Johnson (2012) conducted a simulation of UAS integration into the NAS with controllers and pilots. While controllers reported that UAS pilots responded to communication promptly and appropriately, the controllers also indicated that they used special handling procedures for the UAS aircraft. The controllers also experienced "somewhat higher" workload when managing their sector containing a UAS than the same sector with only manned aircraft. However, the voice software and UAS control software used in this study did not include any latencies that would be expected of UAS operations. Similar to the work by Nadler et al. (1993) and Zingale et al. (2003), it will be important to investigate possible extreme delays to check the sensitivity of other delay conditions. And, although research exists investigating normal and problematic communications between pilots and controllers, few have attempted to measure the duration of delays that controllers judge as acceptable or unacceptable. The present thesis will examine ATCo acceptability ratings of different UAS communication and execution delays to fill this gap in the literature.

Measured Response

There is a growing body of research that is beginning to study the interaction of UAS pilots and ATCos focusing on the topic of measured response (MR). MR has been defined as the end-to-end response time for an aircraft to complete a controller's instruction (Shively et al., 2013). This interaction is divided into several time components from the end of the controller's transmission to the appearance of aircraft executing the instruction on the controller's display. Although there can be different characterization of the MR components, the present study will use the framework provided by Shively et al. (2013). The first MR component (MR1) is measured from the end of the controller's instruction to the beginning of the pilot's verbal response. MR2 is from the end of the controller's instruction to when the pilot begins a control input on the ground control station. MR3 starts when the pilot ends input to the beginning of the aircraft executing the maneuver. MR4 is the time from the aircraft executing the maneuver to the maneuver appearing on the ATCo radar scope (Figure 1).

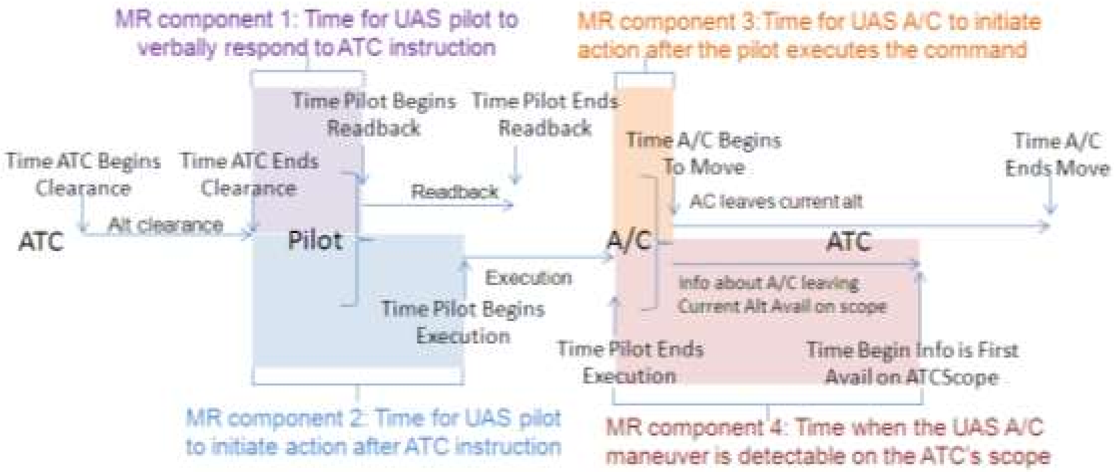

FIGURE 1. Measured response components illustrating ATCo-Pilot interaction. Figure from Shively et al. (2013).

According to Shively et al. (2013) some of the factors contributing to the measured response time include: command, control and communication (C3) architecture; pilot information processing and decision making; aircraft maneuvering; and radar sensitivity and refresh rates. The C3 architecture relays voice transmissions between air traffic management and the pilot (MR1), control inputs from the ground station to the unmanned aircraft (MR 3), and information on the system status of the unmanned aircraft to the ground station. As discussed previously these links have relatively less latency when connected directly by radio frequency line of sight, or greater latencies when operations span the globe mediated through satellite relays. Measured response components 1 and 2 are also subject to the speed with which a pilot processes the information in a controller's instruction, his or her decision to cooperate with the instruction, verbal response, and decision of how and when to carry out the instruction. Elements determining the time at which a maneuver is detectable on the controller's radar screen (MR 4) consist of the sensitivity and refresh rate of the radar system in use, and the performance characteristics of the aircraft performing the maneuver. Understanding how UAS operations differ in terms of measured response will be one step towards incorporating unmanned aircraft into civilian airspace.

Shively et al. (2013) extracted MR components 1, 2, and 4 in a simulation of UAS operating in the NAS. Recruiting 2 ATCos and 14 IFR rated pilots, they instructed controllers to manage one unmanned aircraft in a Los Angeles area TRACON sector. ATCos transmitted a set of 15 commands to the UAS pilot. Two trials of these commands were performed by the controllers and pilots. The instructions involved route amendments, traffic calls, altitude changes, and radio frequency changes. On average pilots initiated their response (MR1) in 2.5 seconds and controllers generally rated their interaction with pilots as acceptable. That is, on a 1 (not acceptable) to 7 (highly acceptable) scale, the mean ratings for all clearance types were above 6. Although the components of MR 1, 2, 4, and the acceptability ratings by controllers were obtained by Shively et al. (2013), these values do not reflect UAS operations in the NAS because both the pilots and controllers were only issuing and responding to clearances. In other words, the controllers were not managing any other traffic, and the pilots were not performing any other tasks. Controller acceptability of the MR components will likely differ in the presence of other traffic and with the addition of the UAS communication and execution delays.

Present Study

As UAS will likely operate with sustained LOS and BLOS links of the ground station and aircraft, the effect of short and long communication and control latencies need to be investigated when interacting with air traffic controllers. Also, as unmanned aircraft move beyond range of LOS or outside satellite coverage, it is necessary to investigate how changing communication and control latencies affect controller's interactions with unmanned aircraft. A simulation study was performed in the Center for Human Factors in Advanced Aeronautics (CHAAT) during February 2013 that was designed to understand how air traffic controllers perceive and adapt to delays they may encounter when interacting with unmanned aircraft in the NAS. The present thesis was a secondary data analysis of the aforementioned simulation. The goal of the thesis was to examine how pilot communication and execution latencies influenced ATC performance, communication, and acceptability ratings of UAS responses when the UAS is operating in a NAS environment.

Specifically, the present thesis examined how short (1.5 sec) and long (5 sec) delays added to the first two MR components, pilot verbal communication latency and pilot execution latency, influenced ATCo performance and their acceptability ratings of the UAS pilots. The specific values for the short and long delays were chosen based on the acceptability ratings collected in Shively et al. (2013), where pilot delays greater than 5 sec were generally rated unacceptable by the ATCos. It was hypothesized that the ATCo performance would be higher when the UAS delays are short than when they are long, and that the ATCo acceptability ratings of the UAS would be higher for short delays than long delays.

In addition to examining the impact of UAS delays, the present study also examined how the predictability of those delays would influence ATCo performance and their acceptability ratings of the pilots by manipulating whether the delays were constant or variable within a scenario. It was hypothesized that if the delays were constant, ATCos could develop strategies for accommodating the UAS. As a result, ATCo performance should be better when the delays are constant than when they are variable, and that the ATCos would rate the UAS communication and execution latencies as more acceptable for constant compared to the variable delay conditions.

CHAPTER 2

METHOD

Design

The present study used a within-subjects design. The independent variables were Voice Delay, Execution Delay, and Delay Consistency. Each independent variable contained two levels. Voice and Execution delays were Short (1.5 seconds) or Long (5 seconds). Predictability was either Constant, using one combination of Voice and Execution delay throughout the trial, or Varied, switching combinations of delays during the trial. Dependent variables were ATCo subjective ratings of their interactions with UAS and conventional pseudopilots. Controller-pilot communications and ATCo performance data were also collected to understand the relation between communications and performance.

Participants

Eight radar-certified Air Traffic Controllers volunteered for this experiment. Participants were compensated $60 per hour for their time. The controllers had a mean of 28 years of military and civilian experience in air traffic management. Six of the participants were recently retired and two were off-duty, active controllers. On a scale of 1 (low) to 7 (high), the controllers rated their experience with the ZLA airspace (M = 4.7), MACS software (M = 3.33), and simulation studies (M = 5.25).

Apparatus

The simulation was conducted in the Center for Human Factors in Advanced Aeronautics Technologies (CHAAT) at California State University, Long Beach. CHAAT includes three separate rooms that were used in the simulation: one room to manage the simulation and run controller participants, a second room for conventional pseudopilot confederates, and the third room for UAS pseudopilot confederates.

For ATCos and conventional pseudopilots the simulation was run using the Multi Aircraft Control System (MACS; Prevot, 2002), creating a medium-fidelity environment. MACS provided a display of the controller's radar scope for sector ZLA 20 (Figure 2), and allowed control of all manned aircraft to pseudopilots. The Multiple UAS Simulator (MUSIM, Figure 3) ground control station was used to allow pseudopilots to control the altitude and point-to-point navigation of the UAS aircraft, callsign PD-1.

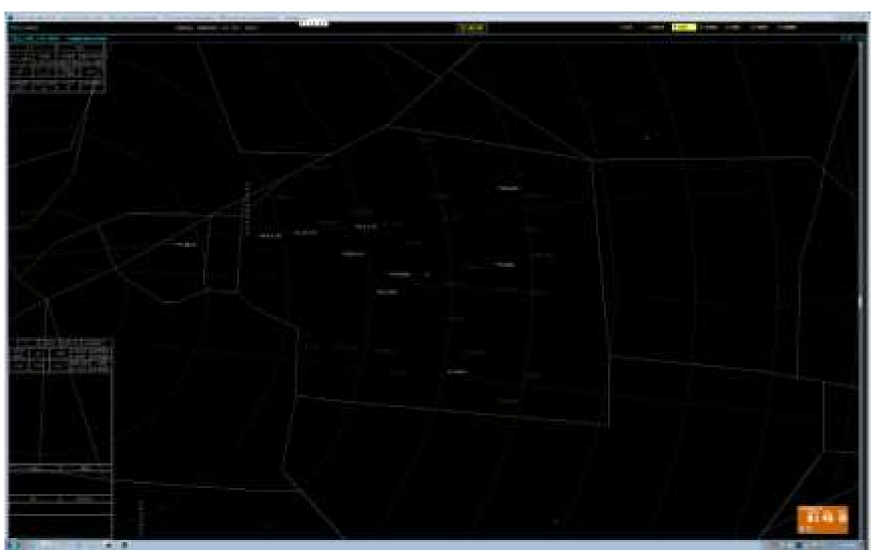

FIGURE 2. MACS Display System Replacement of sector ZLA 20.

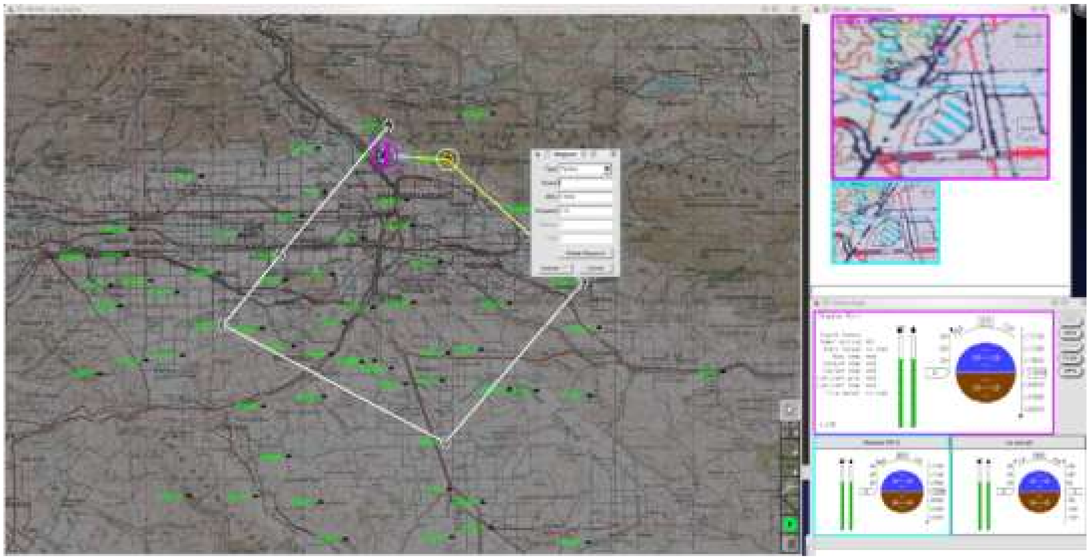

FIGURE 3. MUSIM-UAS pseudopilot interface with initial UAS flight path.

Two parallel worlds were run at a time. Nine computers were required to run each simulated world. The controller's station included two computers, one to simulate the controller's radar scope (Figure 2) and a second small display acting as 'Mission Control' to provide instructions to the controller to direct PD-1 to fixes (Figure 4). The pseudopilot station was manned by two pseudopilots. One pseudopilot was dedicated to checking traffic into the controller's sector and verbally responding to ATCo calls, and managing air traffic outside of sector ZLA 20. The second pseudopilot controlled all aircraft within sector ZLA 20 with the exception of the UAS aircraft.

UAS station consisted of the MUSIM ground control station, and a separate computer used for voice communications, an execution countdown timer, and cockpit situation display (CSD) to provide the UAS pseudopilot traffic information which was not available on the MUSIM ground control station.

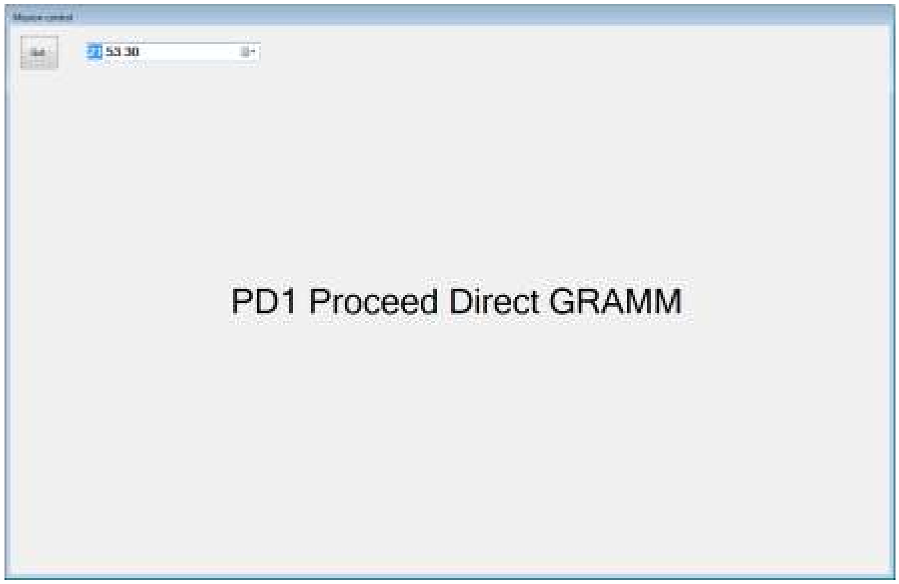

FIGURE 4. Mission Control display. Text instructing ATCo to give UAS (PD-1) clearance to waypoint "GRAMM."

The ATCo, conventional pseudopilots, and UAS pseudopilots spoke to each other using push-to-talk headsets over the voice server. The voice system was modified for the UAS station to include a controlled delay, depending on condition, before transmitting the UAS pseudopilots' message to the ATCo and conventional pseudopilots.

Additional computers were used to manage the simulation software, record communication data between the controller and pseudopilots over the voice service, act as a server for the voice software, and for the ADRS simulation hub. The voice software was modified to simulate blocked transmissions so that if any speaker stepped-on another person speaking the audio from both messages would be mixed and the transmission would be unintelligible for everyone listening on that frequency until only one person was speaking. This simulated a blocked transmission.

Procedure

Each controller participated in the simulation over a two day period. On the morning of the first day participants completed consent forms, demographic questionnaires, and were briefed on simulation procedures. Following the briefing the controllers worked four 30-minute practice trials. The first three trials did not include the UAS aircraft. The fourth trial included the unmanned aircraft in addition to the manned aircraft. The UAS aircraft included no delays transmitting voice or executing commands.

Experimental trials ran for 40-minutes. During the trial controllers managed all air traffic coming into their sector. Controllers were instructed that arrival traffic destined to LAX had priority and were required to leave the sector at an altitude no greater than 12,000 feet, and airspeed 250 knots. The controllers were also told that their sector had a Letter of Agreement to accommodate requests in order to fulfill the UAS, PD-1's, flight objectives while maintaining safe operations for all air traffic.

Approximately 1-2 minutes from the start of the trial and every 4-5 minutes "Mission Control" or the UAS pseudopilot would initiate a route modification request for PD-1. "Mission Control", the screen to the right of the controller's radar scope, would alert the controller through his headset and display a route modification for PD-1 (ex. "PD-1 proceed direct EDITS"). Mission control only requested route modifications direct to fixes for PD-1. The UAS pseudopilot would request only altitude clearances when initiating requests. A total of 8 requests for PD-1 were completed each trial. In alternating order four requests were initiated by the controller/Mission Control, and four initiated by the UAS pseudopilot.

Voice and Execution delays were controlled at the UAS pseudopilot station. Voice software at this station would automatically hold the transmission of the UAS pseudopilot's audio transmission for 1.5 or 5 seconds before broadcasting to the ATCo and manned pseudopilots. The UAS station only included a transmission delay, the UAS pilot had no delay receiving the controller's or manned pseudopilot's transmissions. The controller and conventional pseudopilots had no receiving or transmission delays. Once finished verbally responding to the instruction from the ATCo, the UAS pseudopilot would activate a countdown timer of 1.5 or 5 seconds before beginning to execute the instruction. During the varied delay conditions, the voice and execution delays were advanced to the next delay combination after completing each of the eight clearances (4 Route and 4 Altitude).

After each trial, controllers rated their situation awareness, workload, and experience interacting with the conventional and UAS pseudopilots using an electronic version of the Situation Awareness Rating Technique (SART; Taylor, 1990; Appendix A), NASA Task Load Index (NASA-TLX; Hart, & Staveland, 1987; Appendix B), and a 30 item questionnaire (Appendix C). Once all 8 experimental trials were completed, controllers answered post-simulation and debriefing questionnaires. Finally, the controllers were interviewed during a debriefing session covering the same topics as the debriefing survey.

CHAPTER 3

RESULTS

Analysis

To understand the effects of pilot voice delay, execution delay, and delay predictability on controller's acceptance of UAS operations, analyses were performed on controller performance measures, subjective ratings, and communications. The performance measures could not be extracted for each delay period within the varied delay condition trials. Also, the subjective questionnaires (SART, NASA-TLX, and Post-Trial Questionnaire) were completed at the end of a trial. Therefore, these ratings apply to the whole trial. In these cases, the performance and subjective measures were analyzed for the entire trial, as it was not possible to compare each combination of voice delay and execution delays as a function of predictability. As a result, two analyses were completed for the performance measures and subjective ratings. First, a comparison of the constant delay conditions using a 2 (Voice: short vs. long) by 2 (Execution: short vs. long) within subjects analysis of variance (ANOVA) was performed. Second, a one-way analysis of variance comparing each of the four constant delay conditions and the average of the varied conditions was performed.

Communications measures (step-ons, miscommunications, and measured response components) could be separated for the individual delay combinations during the varied delay condition. Therefore, the effect of delay consistency on controller-pilot communications was analyzed using a 2 (Consistency: constant vs varied) x 2 (Voice:

short vs long) x 2 (Execution: short vs long) repeated measures ANOVA. Due to the small sample size and exploratory nature of this study, alpha was set to $p < .10$ for all analyses.

Communications

Measured response. For each of the eight planned communications between the UAS pilot and controller per trial, the MR components were extracted from data recordings logged by the SimVHF, MACS, and MUSIM software. A total of 64 data points per participants over eight trials were obtained, resulting in 512 data points for the entire simulation. A comparable data set of conventional pseudopilot MR components were extracted from transmissions that occurred close in time to the UAS transmissions. This was done so that the context for communicating with ATCo was relatively equivalent for both UAS and conventional psuedopilots. Table 1 presents UAS and conventional pseudopilot MR 1 and 2 times with the ATCo's acceptability ratings of the delays, computed from the post-trial questionnaire. The introduction of delays for the UAS pilot was fairly successful approximating an additional 1.5 seconds for short delays, and 5 seconds for long delays compared to the conventional pseudopilot MR components. Only the descriptive data are presented here. The analysis of controller acceptability of pilot delays is discussed later in the section for post-trial questionnaires, and a detailed analysis of measured response components can be found in Vu et al. (2013).

Step-ons. The voice software used during the simulation recorded the start and end times of each transmission sent from the controller, UAS pilot, and pseudopilot's computer. Step-ons were recorded whenever two or more people were transmitting at the

TABLE 1. Measured Response Components 1 and 2 for UAS and Conventional Pseudopilot (Pilot), and ATCo Acceptability Ratings.

<table>
<tr><th></th><th>UAS MR1</th><th>Controller Rating</th><th>Pilot MR1</th><th>Controller Rating</th><th>UAS MR2</th><th>Controller Rating</th><th>Pilot MR2</th><th>Controller Rating</th></tr>
<tr><td>Constant</td><td colspan="8"></td></tr>
<tr><td>VS-ES</td><td>2.06 (.165)</td><td>4.75 (.453)</td><td>0.75 (.095)</td><td>5.25 (.526)</td><td>6.05 (.854)</td><td>4.88 (.350)</td><td>3.25 (.725)</td><td>5.25 (.648)</td></tr>
<tr><td>VS-EL</td><td>2.17 (.100)</td><td>4.5 (.627)</td><td>0.80 (.322)</td><td>5.5 (.378)</td><td>10.39 (.471)</td><td>5.13 (.350)</td><td>4.59 (.526)</td><td>5.50 (.327)</td></tr>
<tr><td>VL-ES</td><td>5.50 (.108)</td><td>4.25 (.526)</td><td>0.86 (.11)</td><td>4.63 (.532)</td><td>7.09 (.476)</td><td>4.75 (.701)</td><td>5.60 (1.141)</td><td>5.25 (.313)</td></tr>
<tr><td>VL-EL</td><td>5.48 (.090)</td><td>4.75 (.490)</td><td>1.11 (.172)</td><td>4.75 (.590)</td><td>9.98 (.768)</td><td>4.75 (.491)</td><td>4.50 (.933)</td><td>5.38 (.460)</td></tr>
<tr><td>Varied</td><td colspan="8"></td></tr>
<tr><td>VS-ES</td><td>1.89 (.080)</td><td rowspan="4">4.63 (.486)</td><td>0.72 (.101)</td><td rowspan="4">5.44 (.193)</td><td>7.30 (.476)</td><td rowspan="4">4.88 (.360)</td><td>5.21 (.657)</td><td rowspan="4">5.72 (.186)</td></tr>
<tr><td>VS-EL</td><td>1.98 (.092)</td><td>0.85 (.143)</td><td>10.38 (.509)</td><td>3.25 (1.266)</td></tr>
<tr><td>VL-ES</td><td>5.57 (.071)</td><td>1.12 (.257)</td><td>8.79 (.694)</td><td>5.11 (.922)</td></tr>
<tr><td>VL-EL</td><td>5.56 (.118)</td><td>1.15 (.195)</td><td>10.41 (.478)</td><td>4.50 (.500)</td></tr>
</table>

Note: 1 = Not at all acceptable, 7 = Very acceptable. Mean (*SEM*).

same time. A step-on was attributed to the second and/or third person speaking at the same time as another already transmitting. The total number of step-ons that occurred during a trial was computed as a function of the person committing the step-on on the other speaker. For example, the UAS pilot could commit a step-on by transmitting before the controller had ended his or her transmission. This step-on would be counted as a 'UAS pilot on Controller' step-on.

Voice delays did have a significant effect on the occurrence of step-ons, $F(1, 7) = 4.386$, $p = .074$. There were more step-ons when the UAS pilot responded with a long voice delay (M =4.469, SEM = .941) than with a short voice delay (M = 2.438, SEM =.193). In addition, there was a significant three way interaction of voice delay, and execution delay, and delay predictability on step-ons committed by the UAS pilot $F(1, 7) = 8.149$, $p = .025$. Figures 5 and 6 show the number of step-ons committed by UAS pilots speaking over pseudopilots or controllers. When delays were constant, step-ons by the UAS pilot increased as the voice delay increased from short (M = 2.3755, SEM = .363) to long (M = 4.438, SEM = .764), $F(1, 7) = 5.099$, $p = .058$. The effect of execution delay ($p = .339$), and the interaction of voice delay and execution delay ($p = .418$) were not significant when delays were constant throughout the trial. During the trials in which delays were varied, the interaction of voice and execution delays was significant, $F(1, 7) = 19.250$, $p = .003$. When the execution delays were short, more step-ons occurred when the voice delays were long (M = 6.375, SEM = 1.742) than with a short voice delay (M = 1.625, SEM = .460), $p = .027$. However, no differences in step-ons occurred between short (M = 3.375, SEM = .460) and long (M = 2.625, SEM = 1.133) voice delays when the execution delay was long, $p = .615$. No significant effects of voice delay, execution delay, or delay consistency were found for the number of step-ons committed by pseudopilots and controllers, or for the combined total of step-ons that occurred, $p > .10$.

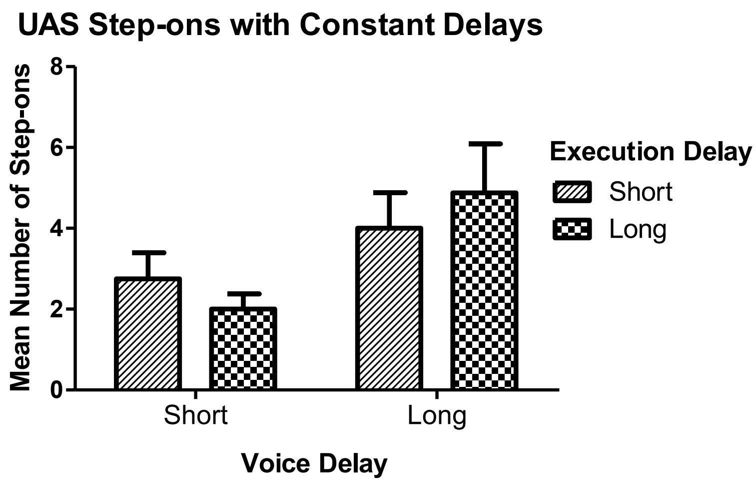

FIGURE 5. Mean number of step-ons committed by UAS pilot during constant delay conditions by voice and execution delay.

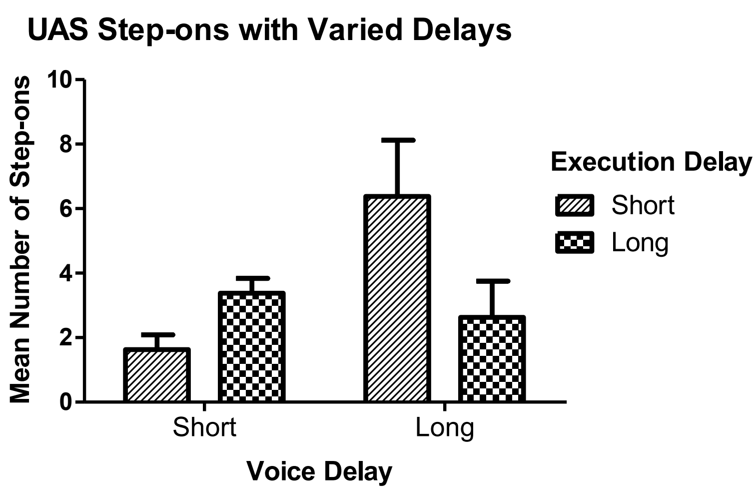

FIGURE 6. Mean number step-ons committed by UAS pilot during varied delay conditions by voice and execution delay.

Miscommunications. Using the transcripts of audio recordings miscommunications were counted based on the need for controllers to repeat an instruction. This would include failure by the pilot to readback the controller's instruction completely or correctly, or to fail to respond to the controller in a timely manner so that the controller reissued the instruction. To identify the interference that delays pose to the success of communications 2 (Voice delay: Short, Long) by 2 (Execution delay: Short, Long) by 2 (Delay consistency: Constant, Varied) repeated measures ANOVA was run on the percentage of communications which were unsuccessful.

For the percentage of miscommunications by the UAS pilot there was a significant interaction between execution delay and delay predictability, $F\,(1, 7) = 5.773$, $p = 0.047$, see Figure 7. When the execution delay was long, more miscommunications were committed by the UAS pilot when the delay was varied ($M = 2.447$, $SEM = 1.097$) than if the delay was constant ($M = .833$, $SEM = .833$), $p = .056$. If the execution delay was short, no significant differences occurred between the constant ($M = 2.288$, $SEM = .910$) and varied ($M = .481$, $SEM = .481$) conditions, $p = .167$.

For all conditions, the mean percentage of miscommunications by the UAS pilot was 1.51 ($SEM = .459$), and the percentage of miscommunications by pseudopilots was 1.22 ($SEM = .129$). While the manipulation of execution delays and delay consistency impacted communications of the UAS pilot with controllers, no effects were found to have changed the occurrence of miscommunications of conventional aircraft pilots, $p > .10$.

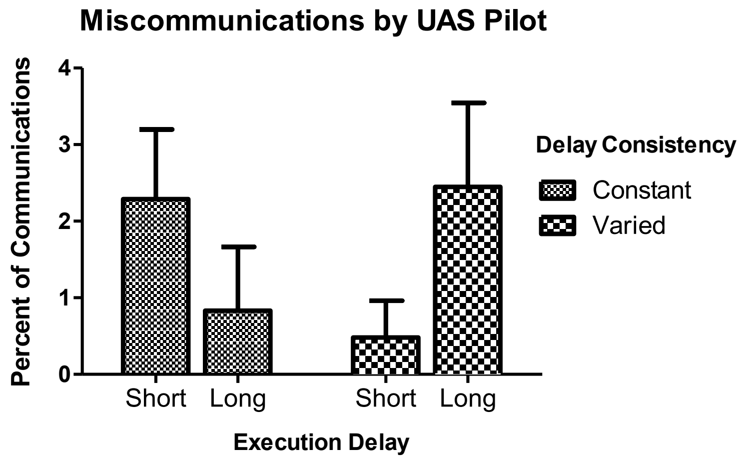

FIGURE 7. Mean percentage of communications with error committed by UAS pilot.

Performance

Controller's performance was measured based on their ability to maintain traffic safety and efficiency. Traffic safety was measured by the number of losses of separation (LOS) that occurred between aircraft pairs. An LOS was counted whenever aircraft violated minimum separation requirements of 5 nautical miles laterally and 1000 feet vertically. Efficiency was measured by the average distance and time that were required for aircraft to travel through the sector.

A one-way ANOVA testing the four constant delays and one variable delay condition, and the 2 (Voice: short or long) x 2 (Execution: short or long) repeated measures ANOVA did not return any significant results for either safety or efficiency, $p > .10$. Considering the complexity of traffic and the disruptive flight path of the unmanned aircraft, controllers performed consistently well during all conditions. On average, 1.45 losses of separation occurred per trial. Although communications were disrupted by miscommunications and step-ons from the delays introduced when interacting with the UAS pseudopilot, controllers were able to move aircraft through the sector at the same level of efficiency and safety. This result corresponds with participants' responses to post-trial questionnaire item 17 which asked them to rate the difficulty of meeting separation and flow requirements. On average, controller's rated the difficulty as moderate ($M = 4.188$), and no significant differences occurred between conditions, $p > .10$.

Post-Trial Questionnaires

At the end of each trial controllers were asked to complete three questionnaires. One questionnaire was the NASA-Task Load Index (NASA-TLX, appendix A) to measure the controller's workload, and a second was the Situation Awareness Rating Technique (SART, appendix B) to measure the controller's situation awareness over the duration of the trial. Last was a 30-item questionnaire that asked the controllers to rate various aspect of their interactions with UAS and conventional pseudo-pilots (Post-Trial Questionnaire, appendix C). Each measure was run in two analyses. One analysis was a one-way ANOVA with 5 levels that included the four constant delay conditions, and the fifth being the average of the four varied delay conditions. The second analysis tested the effects of voice and execution delays for the constant conditions in a 2 (Voice delay: short, long) by 2 (Execution: short, long) repeated measures ANOVA.

Based on the ratings from NASA-TLX and SART, controllers' subjective workload and situation awareness did not different significantly between the factors of voice and execution delay, or delay consistency, $p > .10$.

The post-trial questionnaire included items relating to five general areas. Items 1 through 6 cover acceptability for UAS and pseudopilots phraseology, verbal response delay, and execution delays. Items 7 through 12 asked controllers to rate the predictability and consistency of UAS pilot and pseudopilot's verbal responses and executions to clearances issued by the controller. Items 13 through 15 relate to the controller's workload and situation awareness. Items 16 through 24 were ratings of various aspects of the controller's interaction with the UAS pilot, and conventional pseudopilot. Lastly, items 25 through 30 were to determine the acceptable limits of pilots verbal and execution delays, and for the number of aircraft (manned and unmanned) controllers would be able to manage.

<u>Acceptability.</u> The acceptability items were all rated on a scale from 1 "Not at all acceptable" to 7 "Very acceptable". Overall, the UAS pilot's phraseology (item 1) was on average acceptable to controllers ($M = 5.640$, $SEM = .337$) as were the conventional pseudopilots (item 4; $M = 5.906$, $SEM = .210$). Testing the effects voice and execution during the constant delay conditions with the two-way repeated measures ANOVA was not significant, as was the one-way ANOVA comparing the constant delay conditions with the variable delay condition, $p > .10$.

ATCo ratings of delays for the UAS pilot's verbal response and execution times were all above the middle of the scale (4) (see Table 2). These were typically lower than the ratings for the conventional pseudopilots from the same condition. No significant results were found for the effects of voice delay, execution delay, or the interaction of voice and execution delay for any of the six acceptability items, $p > .10$. Analysis comparing the ratings between UAS and conventional pseudopilots can be found in Vu et al. (2013).

TABLE 2. Controller Acceptability Ratings of UAS and Conventional Pseudopilots' Verbal and Execution Responses.

	UAS Verbal Response	Pilot Verbal Response	UAS Execution	Pilot Execution
VS-ES	4.75 (.453)	5.25 (.526)	4.88 (.350)	5.25 (.648)
VS-EL	4.5 (.627)	5.5 (.378)	5.13 (.350)	5.50 (.327)
VL-ES	4.25 (.526)	4.63 (.532)	4.75 (.701)	5.25 (.313)
VL-EL	4.75 (.490)	4.75 (.590)	4.75 (.491)	5.38 (.460)
Varied	4.63 (.486)	5.44 (.193)	4.88 (.360)	5.72 (.186)

Note: Mean (*SEM*). 1 = Not at all acceptable, 7 = Very acceptable.

Predictability and consistency. Controller ratings for the UAS and conventional pseudopilots' predictability of delays are given in Table 3. Similar to the acceptability rating of MR1 and 2, controllers rated the conventional pseudopilots as more predictable for verbal (items 7 and 9) and execution delays (items 8 and 10). Analyses testing the effects of voice delay, execution delay, or their interaction, and the comparison of the four constant delay conditions and the variable conditions was significant, $p > .10$.

For the consistency of the UAS pilot's verbal delays (item 11) there were no significant effects found with the two-way ANOVA for voice delays, execution delays, and the interaction voice delay and execution delay, or the one-way ANOVA comparing constant delay conditions to the variable condition, $p > .10$. For item 12, the two-way ANOVA voice delay had a significant effect on the controllers' ratings of the UAS pilot's consistency executing maneuvers (item 12), $F(1, 7) = 4.20$, $p = .080$. Controllers rated the UAS pilot as more consistent at executing maneuvers when the voice delay was long ($M = 5.313$, $SEM = .298$) compared to a short voice delay ($M = 4.938$, $SEM = .274$), see Figure 8.

TABLE 3. Controller Ratings of Pilot Verbal and Execution Delay Predictability.

	UAS Verbal Predictability	Pilot Verbal Predictability	UAS Execution Predictability	Pilot Execution Predictability
VS-ES	4.88 (.479)	5.38 (.532)	5.00 (.267)	5.00 (.655)
VS-EL	4.63 (.420)	4.88 (.479)	4.63 (.532)	4.50 (.598)
VL-ES	4.00 (.655)	4.88 (.718)	4.50 (.655)	5.38 (.460)
VL-EL	4.38 (.460)	5.00 (.567)	5.38 (.375)	5.00 (.463)
Varied	4.59 (.395)	5.34 (.306)	4.84 (.398)	5.38 (.236)

Note: Mean (*SEM*). 1 = Not at all predictable, 7 = Very predictable.

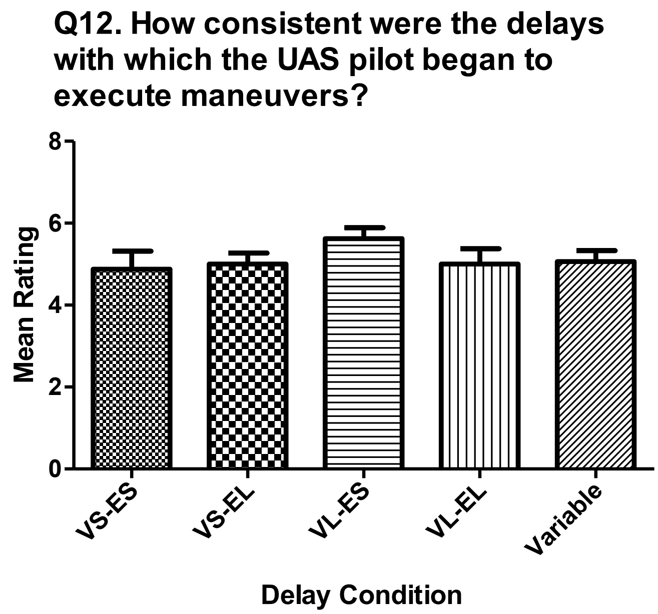

FIGURE 8. Mean ATCo rating of delay consistency for UAS pilot's execution of maneuvers. Note: 1 = Not at all consistent, 7 = Very Consistent.

Workload and situation awareness. Controllers' workload when interacting with the UAS pilot (item 13) ranged from lowest during the long voice, long execution constant condition (M = 4.13, *SEM* = .581) to long voice, short execution condition (*M* = 5.13, *SEM* = .350). The effects of voice delay, execution delay, and their interaction did not significantly affect controller workload, $p > .10$. The moderate to high workload controllers experienced with the UAS pilot can be explained by the disruption to communications caused by delays, and the flight plan of the UAS through the approach path. The controllers' overall workload managing traffic in this simulation (item 14) ranged from 4.75 (*SEM* = .620) to 5.50 (*SEM* = .327) during the long voice, long execution condition and long voice, short execution condition, respectively. Again, no significant effects were found for voice delay, execution delay, and the interaction of voice and execution delays, $p > .10$**.** In general, controllers reported moderate to high workload managing traffic, which was consistent with our goal of designing traffic scenarios to be challenging, but not overwhelming for experienced controllers.

Figure 9 shows the controllers' ratings of their situation awareness when interacting with the UAS pilot (item 15). While there was no effect of either voice or execution delays, the interaction of Voice and Execution delays was significant, $F(1, 7) = 4.20$, $p = .080$. When the voice delay was short, there were no differences in the controllers' ratings of their situation awareness interacting with the UAS pilot, $p = .802$. However, with the UAS pilot on a long voice delay, ratings of situation awareness while interacting with the UAS were less when the execution delay was short ($M = 4.88$, $SEM = .479$) than if the execution delay was long ($M = 5.50$, $SEM = .327$), p = .095. The one-way ANOVA comparing the four constant delay trials and the variable trials was not significant, $F(4,28) = 1.494$, $p = .231$ (Figure 9).

<u>Interaction with UAS and conventional pseudopilots</u>. Previously with item 13, controllers rated their workload interacting with the UAS as moderate to high, however their mean rating for difficulty interacting with the UAS pilots (item 16) was lower at 3.00 ($SEM = .246$). Both the one-way ANOVA testing the four constant and variable conditions, and the 2 (Voice) by 2 (Execution) repeated measures ANOVA were not significant, $p > .10$.

For item 17, comparing their difficulty maintaining separation requirements during normal operations and operations with an unmanned aircraft, controllers viewed the introduction of a UAS as moderately difficult in terms of maintaining the traffic flow and separation requirements ($M = 4.18$, $SEM = .262$). These ratings were not significantly affected by the manipulation of voice delay, execution delay, and their interaction, $p > .10$.

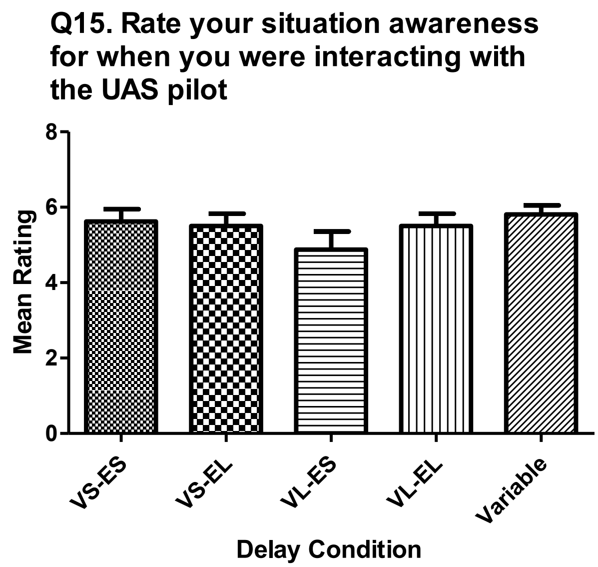

Figure 9. Mean ATCo situation awareness ratings for interaction with UAS pilot. Note: 1 = Very low, 7 = Very high.

Controllers rated their difficulty assessing whether UAS pilots complied with their commands, see Figure 10. The two-way ANOVA for the constant delay conditions resulted in a significant interaction of voice delay and execution delay, $F(1, 7) = 4.950$, $p = .061$. During the long voice delay trials, controllers had greater difficulty assessing if the UAS pilot was executing their commands when the execution delay was short (M = 4.25, SEM = .453) than long (M = 2.50, SEM = .423), $p = .052$. When the voice delay was short, there was no difference for controller's difficulty assessing pilot compliance when execution delay was short (M = 3.00, SEM = .500) than if the execution delay was long (M = 2.88, SEM = .398), $p = .844$. The one-way ANOVA was also significant, F(4,

28) = 2.494, $p = .066$, however t-test for paired comparisons showed no difference between the 5 conditions, $p > .10$.

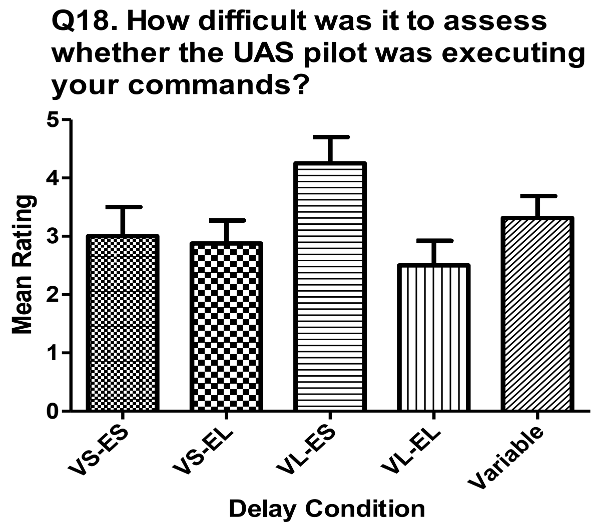

FIGURE 10. Mean ATCo rating of difficulty assessing if the UAS pilot executed commands. Note: 1 = Not at all difficult, 7 = Very difficult.

Questions 19 and 20 asked controllers to rate their ease communicating with the UAS and conventional pseudopilots, respectively. For question 19 there were no significant differences between conditions, $p > .10$. Overall, it was easy for controllers to communicate with the UAS pilots ($M = 4.843$, $SEM = .302$). This was less than the ease of communicating with conventional pseudopilots ($M = 5.86$, $SEM = .238$). Although the UAS delays did not affect the ease of communication with UAS pilots, communication with conventional pseudopilots was affected by the UAS voice delays, $F(1, 7) = 3.798$, $p = .092$. When controllers were asked to rate the ease that they were able to communicate with the pilots of the conventional aircraft (item 20), the short voice delay ($M = 5.938$, *SEM* = .417) was rated as easier than the long voice delay (*M* = 5.250, *SEM* = .509). The effect of execution delays and the interaction of voice delay and execution delay did not significantly affect controllers' ratings of their communications with pilots of conventional aircraft, $p > .10$. Also, the one-way ANOVA revealed no significant differences between the four constant delay conditions and the variable condition, $p = .275$.

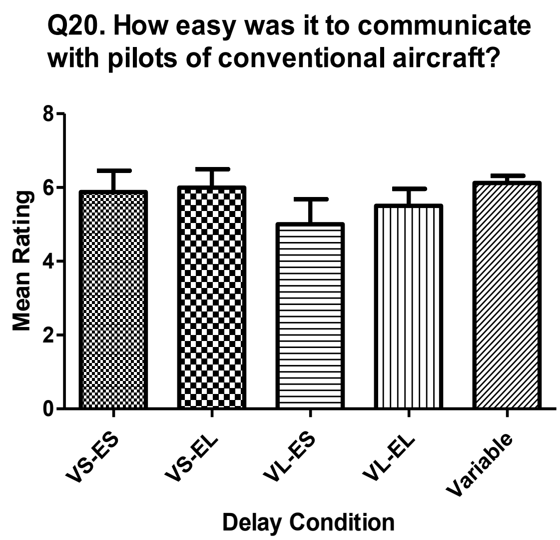

FIGURE 11. Mean ATCo ratings for ease communicating with pseudopilots of conventional aircraft. Note: 1 = Not at all easy, 7 = Very easy.

Figure 12 shows the controllers' ratings for the similarity of the UAS pilot's verbal response delay to that of the conventional pseudopilot's. The main effect of voice delay was significant, $F\ (1, 7) = 6.187$, $p = .042$, but the effect of execution delay was not, $p = .220$. The UAS pilot's delay responding verbally was more similar to the conventional pseudopilot's delay when the voice delays were short (*M* = 4.31, *SEM* =

.647) compared to the long voice delay (*M* = 3.25, *SEM* =.491). The interaction of voice delay and execution delay was also significant $F(1, 7) = 7.631$, $p = .028$. When the UAS pilot verbally responded with only a short delay there was a difference in the effect of execution delays, $p = .041$, such that controllers rated the UAS pilot as more similar to the conventional pseudopilot when the execution delay was short (*M* =4.75, *SEM* = .620) compared to the long execution delay (*M* =3.87, *SEM* = .718). Similarity ratings between short (*M* = 3.00, *SEM* = .567) and long (*M* =3.50, *SEM* = .567) execution delays did not significantly differ when the voice delay was long, $p = .353$. The one-way ANOVA testing the same question with the four constant and combined varied conditions was also significant, $F(4, 28) = 3.298$, $p = .027$, however, t-tests for paired comparisons were not significant, $p > .10$.

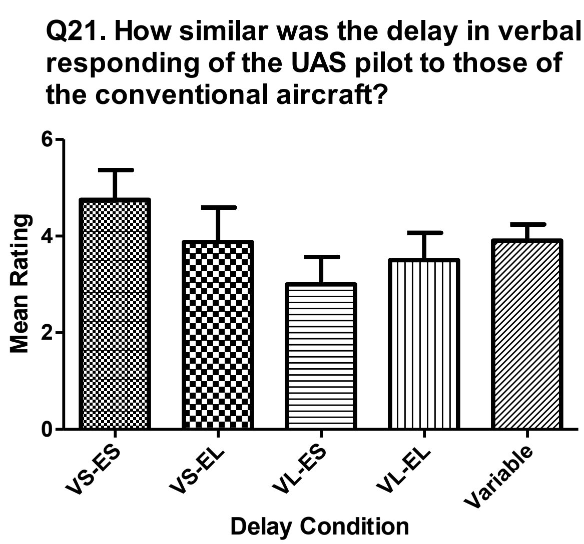

FIGURE 12. Mean ratings of similarity for verbal delays from UAS and conventional pseudopilots. Note: 1 = Not at all similar, 7 = Very similar.

The ratings of similarity of the UAS pilot's delay executing maneuvers to the conventional pseudopilot (item 22) showed no significant effects of voice delay or execution delay, and the comparison of constant trials was also not significant, $p > .10$. Overall the UAS pilot's delay executing maneuvers had a mean rating of 4.23, on the middle of the scale from 1 to 7, the delay executing maneuvers by a UAS pilot were rated somewhat similar to the conventional pseudopilot.

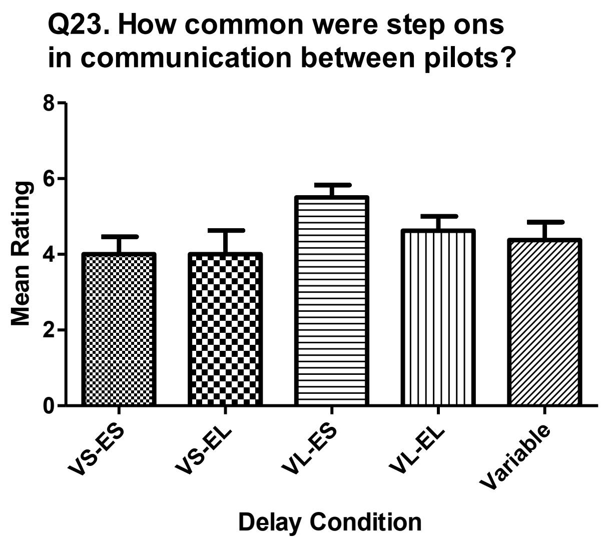

FIGURE 13. Mean ATCo ratings of the frequency of communication step-ons between pilots. Note: 1 = Not at all similar, 7 = Very similar.

In response to question 23, "How common were step-ons/overlaps in communication between pilots", controllers rated that step-ons were more common in the long voice delay condition (*M* = 5.063, *SEM* = .305) than the short delay condition (*M* = 4.00, *SEM* = .433), $F(1, 7) = 5.898$, $p = .046$. This result agrees with the actual number of step-ons the UAS pilot committed which increased as voice delays increased. There were no significant effects for either execution delay or interaction of execution and voice delays, $p > .10$. The one-way ANOVA comparing the variable conditions with the four constant conditions was significant, $F(4, 28) = 2.308$, $p = .083$. We used t-test for paired comparisons and found the long voice delay, short execution delay condition (M = 5.50, SEM = .327) as being rated significantly higher than any of the other delay conditions, $p < .10$. However, the number of step-ons was greatest during the voice long, execution long delay condition (M = 4.875, SEM = 1.127).

For item 24, to prevent conflicts with other traffic, controllers indicated that they did make special accommodations for the UAS aircraft somewhat frequently (M = 4.53, SEM = .296). This is not surprising given that the UAS had several planned conflicts in each traffic scenarios, and the flight path of the UAS was through arrival paths. However, there were no significant differences between delay conditions for the frequency of UAS accommodation, $p > .10$. Although not significant, controllers rated the accommodations during the long voice, long execution delays condition as M = 5.13 (SEM = .398) and for the short voice, long execution condition M =4.13 (SEM = .479).

<u>Managing additional traffic and delays.</u> These next six questions were asked to determine how much more extreme of a situation the controllers would still be able to manage. The first two items asked how many more UAS aircraft the controllers would be able to manage given the delays (voice or execution) they experienced during the trial. For ratings based on the pilot's verbal delay two-way ANOVA found no significant differences between constant conditions for the effects of voice delay, execution delay, or the interaction of the two types of delay, $p > .10$. Also, the one-way ANOVA showed no significant differences between the variable conditions and constant conditions, $p = .665$.

On average, controllers would accept 1–2 additional UAS aircraft when operating on a short voice delay, long execution delay (*M* = 2.13, *SEM* = .227), and the 0 – 1 additional UAS with the short voice delay, short execution delay (*M* = 1.75, *SEM* = .250) or the long voice delay, long execution delay (*M* = 1.75, *SEM* = .366). When the ratings were based on the UAS pilot's delay executing maneuvers the main effect of execution delay was significant, $F(1, 7) = 3.723$, $p = .095$. For the constant delay conditions only, controller's reported that they could have managed more UAS aircraft in their sector when execution delays were long (*M* = 2.00, *SEM* = .164) than if the UAS were operating with a short execution delay (*M* = 1.688, *SEM* = .210), see Figure 14. The main effect of voice delay and the interaction of voice and execution delays were not significant, $p > .10$. The one-way ANOVA comparing the four constant delay conditions and variable delay condition was not significant, $p = .161$.

The next two items asked specifically how much more of a verbal or execution delay from the UAS pilot would the controllers find acceptable. For item 27 relating to the verbal delay there was a significant effect of voice delay, $F(1, 7) = 5.600$, $p = .05$. Not surprisingly, ATCos were more accepting of additional verbal delays after the short verbal delay conditions (*M* = 2.813, *SEM* = .365) compared to the long voice delay conditions (*M* = 2.313, *SEM* = .313), see Figure 15. On the rating scale this comes to an additional 3-4 seconds for the short voice delay conditions, and 1-2 seconds extra for the long delay conditions. This would mean that the upper bound of acceptable voice delay would be 7 seconds from the ratings of the long voice delay, and only 5.5 seconds from ratings of the short voice delay condition.

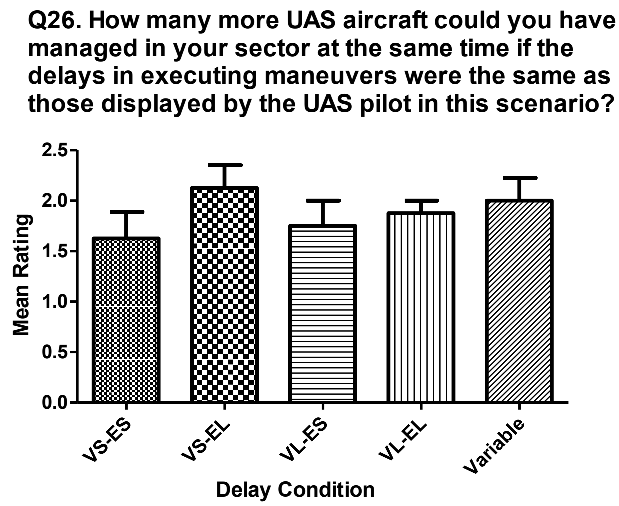

FIGURE 14. ATCo ratings of additional UAS traffic that would be manageable with given execution delays. Note: 1 = 0 UAS aircraft, 2 = 1-2, 3 = 3-4, 4 = 5 6, 5 = 7–8, 6 = 9–10 UAS aircraft.

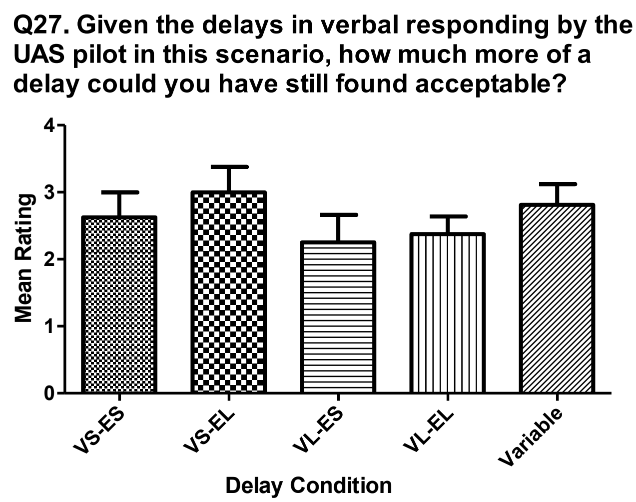

FIGURE 15. Ratings of additional verbal delays that ATCos would still find acceptable. Note: 1 = 0 seconds, 2 = 1-2, 3 = 3-4, 4 = 5 6, 5 = 7–8, 6 = 9–10 seconds.

Comparison of the four constant conditions and aggregate of the variable conditions was significant $F(4, 28) = 2.951$, $p = .037$. Controllers indicated that they would tolerate longer verbal delays in the short voice, long execution delay condition (*M* = 3.00, *SEM* = .378), accepting an additional 3-4 seconds. This was significantly more than the other constant delay conditions, $p < .10$, but not the variable delay condition (*M* = 2.813, *SEM* = .309), $p = .336$. The variable condition was only significantly different from the voice-long, execution-short condition (*M* = 2.250, *SEM* = 3.78), $p = .076$, and ranked between the two short voice delay conditions. No significant differences were found between conditions for effect of execution delay ($p = .227$) or the interaction of voice delay and execution delay, $p = .451$. On average, controllers indicated that latencies of 2-3 additional seconds before pilots began executing commands would be still acceptable (*M* = 2.66, *SEM* = .357). Using these ratings would equate to an MR2 of 9–10 seconds for short execution delays, and 12–13 seconds for long execution delays.

The last two items asked controllers to judge how many additional conventional (manned) aircraft they would be able to manage based on either the execution or verbal delays of the UAS. Neither question resulted in significant effects of voice, execution, nor the interaction of delays, $p > .10$. Also, no significant differences were found for the comparison of the constant delay conditions and the variable delay condition, $p > .10$. Considering the delays in pilot verbal response, controllers rated that they could manage on average 2–3 (*M* = 2.37) additional conventional aircraft. With UAS execution delays in mind, controllers rated that they could again manage 2–3 additional aircraft (*M* = 2.32).

CHAPTER 4

DISCUSSION

As unmanned aircraft are expected to fly alongside manned aircraft, it is crucial to understand how the unique characteristics of UAS will impact the air traffic management system. Because the pilot is not onboard the aircraft, UAS are equipped with control and communication systems that will introduce some delays in responding to instructions from air traffic control (Stansbury et al., 2009). Moreover, the delays in UAS voice communication and command execution can interact and this interaction may result in increased ATCo workload as well as disruptions in ATC workflow. Data on the impact of pilot verbal and execution delays on the measured response of UAS and its impact on ATC will be necessary to develop requirements for integrating UAS into the NAS (Shively et al., 2013).

The purpose of this thesis was to better understand the effect of voice and execution delays on ATCo's acceptance of UAS operations in a NAS environment. Two delay durations were used: short delays were set at 1.5 seconds and long delays at 5 seconds. In addition, the delays were manipulated to be either constant throughout the 40-minute traffic scenario or variable within the scenario. These delay lengths and their predictability were selected to mimic actual latencies that would result from UAS Line of Sight and Beyond Line of Sight control, and with the communication architectures that are likely to be used to connect unmanned aircraft, pilots, and air traffic management in an operational environment.

Influence of Delays in Pilot Verbal Responses and Execution Times

The added delays in our simulation resulted in average UAS MR1 times of 2.1 seconds for the short delay conditions, and 5.5 seconds for the long delay conditions. The additional execution delays led to average MR2 times of approximately 7.3 seconds in the short delay conditions and 10.3 seconds in the long delay conditions. The data obtained in the short verbal delay conditions are within the range found by past studies related to measured response, where the MR1 of manned aircraft resulted in pilots' verbal response to be approximately 1 – 3 seconds in TRACON (Smith, 2008) and En Route (Cardosi, 1993) environments. While studies from Sollenberger et al. (2003) and Rantenen et al. (2004) have also tested the effects of added delays with manned aircraft, however the longest delays used in these studies were roughly equivalent to the average pilot response time found by Cardosi (1993).

We hypothesized that longer delays added to the pilots' verbal and execution initiation times would be more detrimental to ATCo performance, workload, and situation awareness. Although, the long verbal delay conditions resulted in more step-ons than in the short-delay conditions, we found little difference in ATCo's performance, workload, and situation awareness as a function of the delays alone. The lack of observed differences in the present study is likely due to the presence of only one UAS in the sector. With only one UAS, the ATCos were able to make accommodations for the UAS, reducing the impact of the additional delays. Consistent with this assertion, the ATCos indicated in the debriefing sessions that even when the UAS response times were longer than what they would consider to be acceptable, they were still able to make adjustments to other aircraft in the sector to manage their task effectively.

Post-experimental ratings indicated that the ATCos found the delays for UAS pilot's verbal and execution response times to be moderately acceptable (i.e., mean rating above 4, which is the midpoint of the scale), but lower than the pilots of conventional manned aircraft. Although we hypothesized that the ATCo's mean acceptability ratings would be lower for longer delays conditions, we found little difference in the ratings as a function of the amount of additional delay. However, Vu et al. (2013) conducted a detailed analysis of the frequency of the individual ratings, and found that ATCos rated the short verbal delay to be acceptable in more scenarios than the long delays. Thus, there appears to be a preference for shorter delays.

The present study did not provide a mechanism for determining a "red line" for what an acceptable delay is in pilot verbal and execution initiation times. From the post-trial questionnaire, the ATCo's were asked to estimate how much more of an execution or voice delay they would still find to be acceptable. Not surprisingly, ATCos indicated that they could handle a greater additional delay in the short delay conditions than in the longer delay conditions. By combining the MR1 times with the extra allowable time ATCos estimated that they could handle, the upper limit could be as much as 7 seconds for pilot verbal delay. It is important to note, though, that this estimate was for one UAS in the sector, where the ATCo can afford to give the UAS special accommodation.

For execution initiation time, ATCos indicated that the upper bound of 13 seconds after the ATCo issues the clearance may be acceptable. During the debriefing sessions, the ATCos explained why they can handle a longer upper limit for the execution delays in comparison to the verbal delay. First, ATCos are projecting several minutes ahead on the aircraft flight path allowing some time for the pilot to respond. Moreover, while pilots are expected to verbally respond to ATC clearances in a timely manner, the instructions are not expected to be performed instantaneously. Also, some commands include instructions to be performed at a given time such as when the aircraft reaches a certain altitude or crosses a waypoint. For these instances, ATCos do not expect to see immediate changes to the AC. Second, ATCos are not managing one aircraft serially, but a sector of aircraft, and they must be regularly scanning their traffic. After the ATCo issues an instruction and hears the pilot's correct readback they trust the pilot to comply with the instruction. The ATCo will then continue scanning their sector and come back to confirm that the aircraft is performing the correct maneuver. Scanning the sector and returning to the aircraft allows extra time for pilot to perform the maneuver.

Influence of the Predictability of Delays

Although variable delays were hypothesized to be more detrimental than constant delays, there were little differences in ATCo's performance, workload, situation awareness, and acceptability ratings between constant and variable delay conditions. Again, due to the fact that there was only one UAS in the sector, the ATCos were able to compensate when verbal delays and execution delays were unpredictable. Moreover, it is important to note that the effect of delay predictability would be greater if the ATCo-UAS communication resulted in multiple communication exchanges to occur in a brief time. Rantanen et al. (2004) found that pilot verbal delays were more disruptive of performance when multiple exchanges were required between ATCos and pilots. Under these conditions, it would be more important for controllers to be able to predict the length of the delays, especially the delays in verbal responding by UAS pilots, particularly if the delays vary within the same conversation between pilots and controllers. The predictability of the delays would also likely be more important if the controllers were managing multiple UAS in the sector. In the debriefing sessions, the ATCos indicated that they tried to minimize contact to the UAS due to the additional delays associated with the UAS. That is, if the ATCos had a choice between communicating with a UAS or conventional aircraft, they would communicate with the conventional one. The ATCos may not be able to use this strategy to minimize the impact of the delays and their predictability if there were multiple UAS in the sector.

Interaction of Delays with Predictability

Although there was little impact of additional delays and the predictability of the delays on their own, the two variables interacted in several analyses. For step-ons, when delays were constant, the UAS pilots made more step-ons in the long verbal delay conditions than in the short delay conditions. When the delays were varied, the long voice delay and short execution delay resulted in the more step-ons than the other three conditions. Moreover, the ATCos rated their situation awareness to be lower during the long-verbal delay/short-execution delay scenario compared to the other delay combinations. The ATCos also indicated greater difficulty assessing if the UAS pilot was executing their commands in the long-verbal delay/short-execution delay condition compared to the other conditions. In the debriefing sessions, the ATCos reported that they did not like the condition where the verbal delay was long, but execution delay was short because it was possible for the UAS to maneuver before the ATCo has received the readback from the pilot. The ATCos indicated that they would see that the UAS is making a maneuver but they did not know if the pilot correctly understood the instruction. This sequence of events violated ATCos' expectations and bypassed a check in the communication process, which made it less acceptable to the ATCos.

Comparison of UAS versus Conventional Pilots

UAS integration into the NAS calls for a need for UAS to "act and respond as manned aircraft do" (ICAO, 2011, p. 5). In the post-experiment questionnaire, several questions asked the controllers to rate the similarity between UAS and Conventional pilots. ATCos rated UAS pilot's delay responding verbally to be most similar to the conventional pseudopilot's delay when the voice delays were short compared to when they were long. Moreover, with short verbal delays, UAS pilots were rated as more similar to the conventional ones when the execution delay was short. UAS similarity to conventional aircraft did not differ between short and long execution delays. ATCos seem more tolerant of UAS delays compared to conventional pilots. For example, in the verbal delay long/execution delay long condition, the ATCos rated the acceptability of both conventional and UAS pilots to be 4.75, even though the UAS MR1 was over 4 seconds longer than the conventional pilot MR1. The tolerance for longer UAS delays, though, may be reduced if there were multiple UAS in the sector.

Limitations and Future Directions

A key problem facing the integration of UAS in the NAS is specifying what is an acceptable measured response regarding both, pilot verbal responses (MR1) and initiation of commands (MR2). The present study begins to address this issue by comparing short and long delays in each of these two measured response components. However, we were not able to derive a "red line" for acceptability from the present study. The present study selected a short delay which was long enough to not be like the manned aircraft, and the long delay was short enough to not be entirely unacceptable. Overall, we saw consistent performance, SA, and workload across conditions. Some differences in ATCo ratings and the occurrence of communication issues between conditions. Future studies may want to focus on more extreme delays. Groupings of short (<1.5 seconds) and long (between 7 – 12 seconds) voice delays, and longer execution delays would likely result in more significant impact. Moreover, testing longer delays will increase the severity of problems already found or uncover new problems that did not occur during this simulation. And finding delays that still allow UAS to be accepted as conventional aircraft will help determine the technical and procedural gaps that must be bridged for UAS to behave more like convention aircraft.

The present study also only included one UAS in the sector. Because the ATCo participants were highly skilled, they were able to accommodate the UAS by "projecting and protecting" it. The delays in communication and execution initiation of the UAS would be more disruptive with more UAS in the sector. Multiple UAS in the sector would force ATCos to interact more with the UAS, allowing more opportunities for step-ons and for researchers to witness the impact of the different delay parameters.

In the present study, the UAS had set a flight plan that was intentionally disruptive for approach traffic. Although the unpredictability of the flight path may reflect a security or patrol mission, the ATCos indicated that it would not be likely that the UAS with this flight need would be allowed to fly without special handing. Future studies should test delays while incorporating UAS flights with the flow of conventional manned traffic. Flying the UAS on a more cooperative flight path and without a letter of agreement would likely change controllers expectations and acceptance of UAS operations.

APPENDICES

APPENDIX A

SITUATION AWARENESS RATING TECHNIQUE (SART)

Situation Awareness Rating Technique (SART)

Instability of Situation

How changeable is the situation? Is the situation highly unstable and likely to change suddenly (High) or is it very stable and straightforward (Low)?

1 2 3 4 5 6 7

Low High

Complexity of Situation

How complicate is the situation? Is it complex with many interrelated components (High) or is it simple and straightforward (Low)?

1 2 3 4 5 6 7

Low High

Variability of Situation

How many variables are changing within the situation? Are there are large number of factors varying (High) or are there very few variables changing (Low)?

1 2 3 4 5 6 7

Low High

Arousal

How aroused are you in the situation? Are you alert and ready for activity (High) or do you have a low degree of alertness (Low)?

1 2 3 4 5 6 7

Low High

Concentration of Attention

How much are you concentrating on the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?

1 2 3 4 5 6 7

Low High

Division of Attention

How much is your attention divided in the situation? Are you concentrating on many aspects of the situation (High) or focused on only one (Low)?

1 2 3 4 5 6 7

Low High

Spare Mental Capacity

How much mental capacity do you have to spare in the situation? Do you have sufficient capacity to attend to many variables (High) or nothing to spare at all (Low)?

1	2	3	4	5	6	7
Low						High

Information Quantity

How much information have you gained about the situation? Have you received and understood a great deal of knowledge (High) or very little (Low)?

1	2	3	4	5	6	7
Low						High

Information Quality

How good is the information you have gained about the situation? Is the knowledge communicated very useful (High) or is it a new situation (Low)?

1	2	3	4	5	6	7
Low						High

Familiarity with Situation

How familiar are you with the situation? Do you have a great deal of relevant experience (High) or is it a new situation (Low)?

1	2	3	4	5	6	7
Low						High

APPENDIX B

NASA TASK LOAD INDEX (NASA-TLX)

NASA Task Load Index (NASA-TLX)

Mental Demand

How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Low																			High

Physical Demand

How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low																			High

Temporal Demand

How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

Low																			High

Performance

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Low																			High

Effort

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low																			High

Frustration

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low																			High

APPENDIX C

POST-TRIAL QUESTIONNAIRE

Post-trial Questionnaire

1. How acceptable was the UAS pilot's phraseology when communicating with you?

1	2	3	4	5	6	7
Not at all acceptable						Very acceptable

2. How acceptable were the delays in the UAS pilot's verbal response to your commands and clearances?

1	2	3	4	5	6	7
Not at all acceptable						Very acceptable

3. How acceptable were the delays with which the UAS pilot began to execute maneuvers?

1	2	3	4	5	6	7
Not at all acceptable						Very acceptable

4. How acceptable was the conventional pilot's phraseology when communicating with you?

1	2	3	4	5	6	7
Not at all acceptable						Very acceptable

5. How acceptable were the delays in the conventional aircraft pilots' verbal responses to your commands and clearances?

1	2	3	4	5	6	7
Not at all acceptable						Very acceptable

6. How acceptable were the delays with which the pilots of conventional aircraft began to execute maneuvers?

1	2	3	4	5	6	7
Not at all acceptable						Very acceptable

7. How predictable were the delays in the UAS pilot's verbal response to your commands and clearances?

1	2	3	4	5	6	7
Not at all						Very

predictable predictable

8. How predictable were the delays with which the UAS pilot began to execute maneuvers?

1 2 3 4 5 6 7

Not at all predictable — Very predictable

9. How predictable were the delays in the conventional aircraft pilots' verbal responses to your commands and clearances?

1 2 3 4 5 6 7

Not at all predictable — Very predictable

10. How predictable were the delays with which the conventional aircraft pilots began to execute maneuvers?

1 2 3 4 5 6 7

Not at all predictable — Very predictable

11. How consistent were the delays in the UAS pilot's verbal response to your commands and clearances?

1 2 3 4 5 6 7

Not at all consistent — Very consistent

12. How consistent were the delays with which the UAS pilot began to execute maneuvers?

1 2 3 4 5 6 7

Not at all consistent — Very consistent

13. Rate your workload for when you were interacting with the UAS pilot.

1 2 3 4 5 6 7

Very low — Very high

14. Rate your overall workload when managing all traffic in this scenario.

1 2 3 4 5 6 7

Very low — Very high

15. Rate your situation awareness for when you were interacting with the UAS pilot.

1	2	3	4	5	6	7
Very low						Very high

16. How difficult was it to interact with the UAS pilot?

1	2	3	4	5	6	7
Not at all difficult						Very difficult

17. How difficult was it to meet flow and separation requirements with a UAS in your sector compared to normal operations?

1	2	3	4	5	6	7
Not at all difficult						Very difficult

18. How difficult was it to assess whether the UAS pilot was executing your commands?

1	2	3	4	5	6	7
Not at all difficult						Very difficult

19. How easy was it to communicate with the UAS pilot?

1	2	3	4	5	6	7
Not at all easy						Very easy

20. How easy was it to communicate with pilots of conventional aircraft?

1	2	3	4	5	6	7
Not at all easy						Very easy

21. How similar was the delay in verbal responding of the UAS pilot to those of the conventional aircraft?

1	2	3	4	5	6	7
Not at all similar						Very similar

22. How similar was the delay in executing maneuvers by the UAS pilot to those of pilots of the conventional aircraft?

1	2	3	4	5	6	7

Not at all similar — Very similar

23. How common were step ons/overlaps in communication between pilots?

1	2	3	4	5	6	7

Not at all common — Very common

24. How often did you have to make special accommodations for the UAS to prevent conflicts?

1	2	3	4	5	6	7

Never — Very often

25. How many more UAS aircraft could you have managed in your sector at the same time if the delays in verbal responding were the same as those displayed by the UAS pilot in this scenario?

0	1-2	3-4	5-6	7-8	9-10

UAS aircraft — UAS aircraft

26. How many more UAS aircraft could you have managed in your sector at the same time if the delays in executing maneuvers were the same as those displayed by the UAS pilot in this scenario?

0	1-2	3-4	5-6	7-8	9-10

UAS aircraft — UAS aircraft

27. Given the delays in verbal responding by the UAS pilot in this scenario, how much more of a delay could you have still found acceptable?

0	1-2	3-4	5-6	7-8	9-10

seconds — seconds

28. Given the delays in executing maneuvers by the UAS pilot in this scenario, how much more of a delay could you have still found acceptable?

0	1-2	3-4	5-6	7-8	9-10

seconds — seconds

29. Given the delays in verbal responding by the UAS pilot in the present scenario, how many more conventional aircraft would you have been able to manage in your sector during the scenario?

0	1-2	3-4	5-6	7-8	9-10
aircraft					aircraft

30. Given the delays in executing maneuvers by the UAS pilot in the present scenario, how many more conventional aircraft would you have been able to manage in your sector during the scenario?

0	1-2	3-4	5-6	7-8	9-10
aircraft					aircraft

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