

Validation of Minimum Display Requirements for a UAS Detect and Avoid System

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The full integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS), a prerequisite for enabling a broad range of public and commercial UAS operations, presents several technical challenges to UAS developers, operators and regulators. A primary barrier is the inability for UAS pilots (situated at a ground control station, or GCS) to comply with Title 14 Code of Federal Regulations sections 91.111 and 91.113, which require pilots to “see and avoid” other aircraft in order to maintain well clear. UAS pilots’ removal from the flight deck of the aircraft necessitates the development of a UAS-specific system for detecting nearby traffic and displaying traffic information to the pilot to support their ability to maintain an objectively defined “DAA well clear” threshold from other aircraft. This new UAS-specific function of remaining DAA well clear is called traffic avoidance. The resulting Detect and Avoid (DAA) system, however, will be subject to a collection of requirements that manufacturers will be obligated to meet in order to certify their equipment. RTCA Special Committee 228 (SC-228), a consortium of representatives from government, industry and academia, is responsible for developing and documenting the Minimum Operational Performance Standards (MOPS) for UAS DAA systems. The present study is the final in a series of human-in-the-loop (HITL) experiments designed to explore and test the various display and alerting requirements being incorporated into the DAA MOPS. Whereas the prior DAA HITLs examined a wide variety of DAA display features and concepts, the current experiment aims to validate the latest minimum display requirements for Phase 1 of the DAA MOPS. Rather than test different display concepts, this study tests two configurations of a MOPS-compatible DAA display: a version that is integrated into the primary navigation and control display of the GCS and a version that is physically separated from the primary display. This manipulation tests the draft minimum requirement that allows the DAA traffic display to be a separate, or standalone, configuration. This type of configuration is a more achievable near-term technology solution since it does not stipulate additional certification or integration requirements on UAS manufacturers. However, a standalone display configuration has the potential to result in pilot performance issues resulting from the cognitive costs of switching between the primary DAA display and the primary navigation and control display. This configuration is also particularly susceptible to errors if the displays are in different orientations (e.g., north-up versus track-up). Both the integrated and standalone display configurations were presented to 16 active UAS pilots in a medium-fidelity simulation, which included confederate air traffic controllers and pseudo pilots operating simulated manned traffic. Pilots were tasked with navigating two different mission routes while maintaining DAA well clear with scripted conflicts. Pilot response times (i.e., measured response) and ability to remain DAA well clear are reported. Primary results indicate that both display configurations resulted in favorable response times and well clear rates. While there were clear trends of pilots objectively performing better in the integrated display condition, with several measured response metrics reaching statistical significance, the differences between the two displays were typically moderate. While the primary variable of DAA display location did not have an especially large impact on pilot performance on its own, when examined alongside the type of DAA threat the pilot was facing (a caution-level versus a warning-level alert), the response time benefits associated with the integrated display were amplified. The implications of these

results on the Phase 1 DAA MOPS and the connection of this data to previous studies is also discussed.

I. Introduction

In the last several years, there has been a steep increase in research and development activities dedicated to supporting broader access of Unmanned Aircraft Systems (UAS) within the United States' National Airspace System (NAS). Driven by both public and private interests, the end goal of these activities is to enable a wide variety of UAS operations and missions through full integration with manned aircraft in all classes of airspace. One of the most visible efforts to further the integration of UAS in the NAS has been RTCA Special Committee 228 (SC-228), Minimum Operational Performance Standards (MOPS) for UAS¹. This consortium of subject matter experts from government, industry, and academia has spent the last four years developing technical requirements for two critical technology areas for UAS integration into the NAS as identified in the 2013 comprehensive roadmap produced by the Federal Aviation Administration (FAA)²: command and control (C2), and detect and avoid (DAA). Addressing these two critical technology areas will help overcome major technical barriers for safe operation of UAS in civil airspace that are uniquely associated with the removal of the pilot from onboard the aircraft.

The C2 MOPS development has focused mainly on the technical requirements for supporting the command and control function of the UAS from the ground control station (GCS) through the data link for NAS operations. While some human systems integration considerations have been accounted for (e.g., the acceptable amount of latency and the display of the data link status to the pilot), the bulk of the pilot in the loop considerations for UAS operations in the NAS are contained within the DAA MOPS. Specifically, the DAA MOPS are intended to provide a means of compliance with Title 14 Code of Federal Regulations sections 91.111 and 91.113 which require pilots of manned aircraft to, 1) not operate so close to another aircraft as to create a collision hazard, and, 2) "see and avoid" other aircraft while operating under both instrument and visual flight rules³. In order to meet both of these requirements, pilots of manned aircraft are expected to maintain "well clear" of other aircraft, a function that is typically accomplished by onboard pilots applying a subjective judgment of separation via out-the-window visual acquisition of nearby aircraft. For UAS, the DAA system will assist UAS pilots in maintaining an objectively defined DAA well clear threshold from other aircraft (i.e., "DAA well clear"). The UAS function of maintaining an objectively defined DAA well clear threshold from other aircraft is called "traffic avoidance".

The DAA system specified within the SC-228 MOPS is explicitly intended to enable pilots of UAS, located at a ground-based control station, to perform the traffic avoidance function by providing essential information on electronic displays. With their removal from the aircraft, and the concomitant ability to visually acquire nearby aircraft, this information will be the primary basis from which to execute the three primary traffic avoidance functions: 1) detect potential threats to loss of DAA well clear, 2) determine an appropriate resolution maneuver to avoid a loss of DAA well clear, and 3) execute that maneuver. Thus, it is critical for the safety assurance of future DAA-equipped UAS that the DAA system provide sufficient information to UAS pilots to support their ability to perform these three functions.

The study reported in this paper is the last in a series of human in the loop (HITL) experiments conducted by the authors with the explicit intent to inform the development and validation of the minimum display requirements for the Phase 1 DAA MOPS being developed by SC-228. This series of studies has been primarily focused on evaluating the effect of different maneuver guidance display configurations on pilot performance of the traffic avoidance function, although other display features, such as alerting levels and thresholds and information elements, have also been investigated. The first four HITL experiments provided the empirical basis for the drafting of an initial set of minimum DAA display requirements^{4,5,6,7}. The purpose of the experiment reported here was to provide validation of those requirements. In order to evaluate pilots' performance of the traffic avoidance function both within and between experiments, a common set of objective metrics have been developed that capture operationally relevant aspects of this performance.

A. Quantifying Pilot Performance of the Traffic Avoidance Function

Pilot performance of the traffic avoidance function has been quantified using two categories of metrics: measured response and loss of DAA well clear. The first, measured response, is important to understand given that a potential loss of DAA well clear event is always constrained temporally. The amount of time that a pilot has to avoid a loss of DAA well clear is limited by several factors, such as operational rules, alerting thresholds, the performance of the surveillance equipment, and the encounter geometry. While a traffic avoidance hazard is not as urgent as a collision avoidance hazard, timely response by pilots will still be critical to effectively maintain DAA well clear of other

aircraft. At the same time, it doesn't matter how quickly a pilot is able to maneuver in response to a loss of DAA well clear threat if they fail to resolve the threat. Thus, pilot response times must be understood alongside an assessment of their ability to successfully manage the traffic avoidance function; this performance is captured by several different loss of DAA well clear metrics. Both categories of metrics are discussed in turn below.

Measured response captures the end-to-end response for a UAS pilot to complete the traffic avoidance functions by breaking the response into discrete stages, from the issuance of a DAA alert, until the pilot uploads a final resolution maneuver (i.e., "the pilot-DAA timeline"). Measured response was initially developed to capture the response of UAS pilots complying with an air traffic controller's (ATC) clearance^{8,9}, however, it has been subsequently adapted for the DAA traffic avoidance function. The main stages of the pilot-DAA timeline are shown Table 1.

Table 1. Stages of the pilot-DAA interaction timeline (reprinted with permission from Fern et al.⁴).

Stage	Description
T ₀	DAA (traffic avoidance) alert appears on the display
T ₁	Pilot notifies ATC of traffic and requests to maneuver around threat
T ₂	ATC (nominally) approves pilot's request to maneuver
T ₃	Pilot begins interacting with GCS vehicle control interfaces to initiate a maneuver
T _{4a}	Pilot uploads first maneuver to aircraft
T _{4b}	Pilot uploads final maneuver to aircraft

The use of measured response for evaluating different display configurations provides insight into how different display features affect different stages of the pilot-DAA timeline by allowing for the extraction of various metrics, or response times, between individual stages. For example, different display configurations may impact the time that it takes pilots to initiate a maneuver response in the GCS following the appearance of the alert ($T_3 - T_0$; i.e., initial response time), or the time it takes the pilot to upload the final maneuver response using GCS control interfaces ($T_{4b} - T_3$, i.e., total edit time). Measured response supports the ability for researchers to identify these differential effects of display features on pilot performance.

Measured response is also critical in determining the pilot contribution to the overall traffic avoidance timeline. The amount of time that pilots need to execute a maneuver in response to a loss of DAA well clear threat has a direct impact on other system requirements such as alerting thresholds and surveillance performance. As pilot response times increase, so too must the alerting thresholds, and in turn, the range requirements for the onboard surveillance equipment. This is particularly important for the future UAS DAA system, which will require an active onboard RADAR to detect non-cooperative aircraft (i.e., those not broadcasting their position with a transponder). Longer detection ranges correspond to greater size, weight and power requirements, which can limit the types of aircraft able to equip with such a RADAR and can stress the state-of-the-art of this very new technology. Given these considerations, the pilot's role in the system needs to be quantified in order to ensure that the other components of the DAA system will be able to provide the necessary information to the UAS pilot via the DAA display; measured response provides this capability.

The loss of DAA well clear metrics provide the most direct operational measure of how well pilots perform the traffic avoidance task. The primary metric is the proportion of encounters that resulted in an actual loss of well clear when one was predicted. Here, only encounters where pilots had sufficient time to avoid the loss of DAA well clear, based on pilots' measured response and the time to loss of DAA well clear at first alert, but failed to do so, are counted against the pilot. Instances of a loss of DAA well clear can also be categorized in order to determine the source of the pilots' failure. This allows researchers to diagnose the loss of well clear and helps to identify any specific deficiencies with different display configurations. Finally, the severity of losses of well clear are also determined using a separation index¹⁰. This index provides insight into the extent that the well clear volume was penetrated. This measure acknowledges that not all losses of well clear are equivalent and that some display configurations may help reduce the severity of well clear violations without reducing their overall frequency.

B. Previous Research on DAA Displays

The four previous HITL simulations conducted in support of the SC-228 DAA display MOPS have shown that both the measured response and loss of well clear metrics are sensitive to different display configurations and are therefore useful for evaluating pilot performance^{4,5,6,7,11,12}. As mentioned previously, a primary goal of these prior experiments was to evaluate the effect of various maneuver guidance display configurations on pilot performance in order to determine which configuration(s) constituted the minimum requirement(s) for the DAA MOPS. Maneuver

guidance is a form of decision aiding that is intended to assist the pilot in choosing a maneuver that will resolve a conflict; in the case of the UAS DAA system, the conflict is a predicted loss of DAA well clear threat. Maneuver guidance display configurations can be described as falling into one of three general categories: informative, suggestive, and directive. An informative display is one in which only informational elements are depicted; no maneuver guidance recommendations are provided. A suggestive display configuration provides pilots with a range of maneuver options that are predicted to resolve a conflict, allowing them to select the option that best satisfies their needs. Finally, a directive display configuration provides a single recommended maneuver which the pilot is expected to follow.

The presence and nature of the maneuver guidance to be required of future DAA systems was a critical question for the SC-228 MOPS. The community was responsible for specifying only those minimum requirements necessary to support the safe operation of a UAS equipped with a DAA system while leaving design flexibility to manufacturers. While some members of the committee felt that pilots could effectively perform the traffic avoidance function with a basic informative DAA display [similar to existing cockpit displays of traffic information (CDTIs)], others felt that an automatic or autonomous DAA capability would be required (i.e., that a pilot in direct control of a UAS would be unable to perform the task at all). Complicating this debate was that there was very little data or understanding about how UAS pilots would actually execute the traffic avoidance function, given a newly accepted DAA well clear threshold¹³. As such, it was paramount to evaluate pilot performance of the traffic avoidance function given various maneuver guidance displays in a relevant environment.

In the first of the series of HITL experiments, Fern et al.⁴ compared two levels of DAA display location (standalone versus integrated) and two levels of DAA display information level (basic versus advanced). Their results indicated that while there were no significant effects of display location on pilot performance, information level did have a significant effect on pilots' measured response. Specifically, the advanced display configurations, which included basic information elements (e.g., intruder location and directional information, relative altitude, speed, etc.), advanced alerting logic, and two types of maneuver guidance - suggestive maneuver guidance (in the form of vector planning tools, which allow pilots to query proposed headings and altitudes for predicted conflicts), and directive maneuver guidance (in the form of "auto-resolutions" which provide a single recommended maneuver, e.g., "Fly Heading 160") - resulted in significantly shorter response times than the basic display configurations, which included only basic alerting logic and information elements. There were no significant effects of information level on the proportion or severity of losses of DAA well clear (reported by Santiago and Mueller¹¹), although there was a trend toward better performance for the advanced display configurations. Unfortunately, because of the wide variety of additional features in the advanced display configurations compared to the basic condition, the authors were unable to pinpoint which specific features contributed to an improvement in pilots' objective performance.

Rorie and Fern⁵ conducted a follow-on experiment in order to attempt to identify the differential effects of two of the primary display features implemented by Fern et al.⁴: suggestive maneuver guidance in the form of vector planner tools, and directive maneuver guidance in the form of auto-resolutions. In this experiment four display configurations were compared: an informative display, a suggestive display (with the vector planner), a directive display (with the auto-resolutions), and a combined suggestive and directive display (allowing for a comparison to the advanced display configuration in Fern et al.). The results of Rorie and Fern indicated that the improvement in pilots' measured response seen in Fern et al. were largely the result of the directive maneuver guidance tool (i.e., auto-resolutions). While there were no significant effects of display configuration on pilots' measured response or loss of DAA well clear metrics (reported by Santiago and Mueller¹¹), both of the directive maneuver guidance display configurations trended toward better overall performance, (i.e., shorter response times, and lower proportions and severity of losses of DAA well clear). However, the authors argued that it was not only the presence of directive maneuver guidance that contributed to improved pilot performance. Rather, it was the coupling of the directive maneuver guidance with the GCS vehicle control interfaces. As implemented, the maneuver recommended by the directive guidance was automatically input into the relevant entry field of the navigation interface, requiring pilots to simply execute the recommended maneuver if they deemed it satisfactory. Thus the comparison between the informative and suggestive display configurations, which required pilots to manually input their resolution maneuver, and the two directive display configurations, where pilots pressed one button to accept and execute the resolution maneuver, was not a direct one. In addition, feedback from SC-228 indicated that the acceptance of directive maneuver guidance as a minimum requirement for the DAA MOPS was unlikely. Of primary concern was the amount of development and validation effort that would be required for a system that issues a single recommended maneuver that is presumed to be safe. The Traffic alert and Collision Avoidance system (TCAS), for example, provides directive maneuver guidance to pilots of manned aircraft to avoid a near mid air collision (NMAC), and was subject to more than a decade of research, development and validation¹⁴. With a suggestive maneuver guidance display, however, the responsibility for determining a safe maneuver resides, ultimately, with the pilot in command, limiting the DAA system's liability.

Following the results of Fern et al.⁴ and Rorie and Fern⁵, and the considerations of the SC-228 committee, Rorie, Fern and Shively⁶ evaluated the effect of three different suggestive maneuver guidance display configurations on pilot performance against a baseline informative display configuration. The suggestive display configurations included a vector planner display similar to what was tested in the previous two HITLs, and two “banding” display configurations. As opposed to the vector planner display, which required pilots to manually test proposed headings and altitudes to resolve conflicts, the banding display configurations provided pilots with continuous information about the predicted threat level for all possible headings and nearby altitudes or vertical rates. The results of the Rorie, Fern and Shively showed significantly better pilot performance for the banding suggestive maneuver guidance displays compared to the informative display across both the measured response and loss of DAA well clear metrics (reported by Mueller, Santiago and Watza¹²). Pilots using the vector planner suggestive maneuver guidance display outperformed the informative display but did not reach the level of performance of the two banding displays. The results of this experiment provided objective support for the inclusion of suggestive maneuver guidance in the form of banding as a minimum requirement for the DAA system, and was included in an early draft of the SC-228 DAA MOPS.

In addition to providing support for the inclusion of suggestive guidance as a minimum requirement, the experiment conducted by Rorie, Fern and Shively⁶ highlighted a gap in the maneuver guidance concepts that had thus far been tested by the authors. While both banding suggestive maneuver guidance displays provided guidance to *maintain* DAA well clear, only one was designed to account for when a loss of DAA well clear could no longer be prevented. For the other banding display, a gap occurred when the DAA well clear threshold was crossed or about to be crossed, and there were no viable trajectories that could be achieved to maintain DAA well clear. The result on the DAA display was that no recommended maneuvers were available to the pilot to *regain* well clear – precisely at the point when a safe maneuver was most critical. In addition, although one banding display did provide continuous guidance through an actual loss of well clear event, pilot performance in response to this type of guidance (i.e., to regain well clear) was not specifically studied or measured. The lack of DAA maneuver guidance to regain well clear in one banding display, and the incomplete assessment of the impact of this feature on pilot performance in the other banding display, underscored its criticality and the need for further studies on its presentation.

Different display designs for depicting maneuver guidance to regain DAA well clear were evaluated by Monk and Roberts⁷. (In this experiment, researchers modified the banding display configuration from Rorie, Fern and Shively⁶ that did not originally contain any maneuver guidance to regain DAA well clear.) During encounters where a loss of DAA well clear could no longer be avoided, one of two forms of additional maneuver guidance (i.e., “DAA well clear recovery” guidance) was presented to pilots on their integrated traffic display. This guidance was intended to assist the pilot in maximizing separation at closest point of approach and avoid an NMAC. Due to the infrequent occurrences of losses of well clear with this banding display in the prior study, some intruder aircraft were scripted to ‘blunder’ into ownship with sudden changes in trajectory to ensure that losses of well clear occurred (allowing for the presentation of DAA well clear recovery guidance). The guidance configurations recommended either a horizontal or vertical maneuver with a textual command and one of two different graphical formats: Limited Suggestive and Directional. Limited Suggestive guidance displayed small ranges of altitudes or headings to fly in order to regain DAA well clear (i.e., smaller than those provided by the maneuver guidance to maintain DAA well clear), while the Directional guidance displayed an arrow indicating the general direction of the recommended horizontal (left/right) or vertical (climb/descend) maneuver – thus, leaving the maneuver size to pilot discretion. Both guidance designs yielded identical results in the DAA well clear metrics when the DAA well clear threshold was penetrated. There were also no differences in pilot response times or compliance rates between the two DAA well clear recovery displays; overall, pilots complied with the guidance 97% of the time. The lack of performance effects between designs and pilot feedback indicated that there are multiple acceptable methods of displaying continuous suggestive guidance when the range of maneuver options becomes limited in these severe encounter cases.

The previous four HITL simulations summarized above provided empirical support for the development of a draft set of requirements for the traffic display detailed within the DAA MOPS, especially those related to the display of maneuver guidance to maintain and regain DAA well clear [several requirements related to information elements came from the minimum operational performance standards (MOPS) for aircraft surveillance applications (ASA) system¹⁵]. The purpose of the current experiment was to validate the pilot performance of the traffic avoidance function given the final draft set of requirements as informed by the previous experiments. In addition, this experiment re-examined the effect of display location on pilot performance. Although this had been studied in the original HITL experiment by Fern et al.⁴, the authors felt that it deserved further investigation given that the draft DAA MOPS specified that a non-integrated (i.e., collocated with the native GCS displays), or standalone, display was allowable under the minimum requirements, and the three HITLs since had utilized an integrated display configuration.

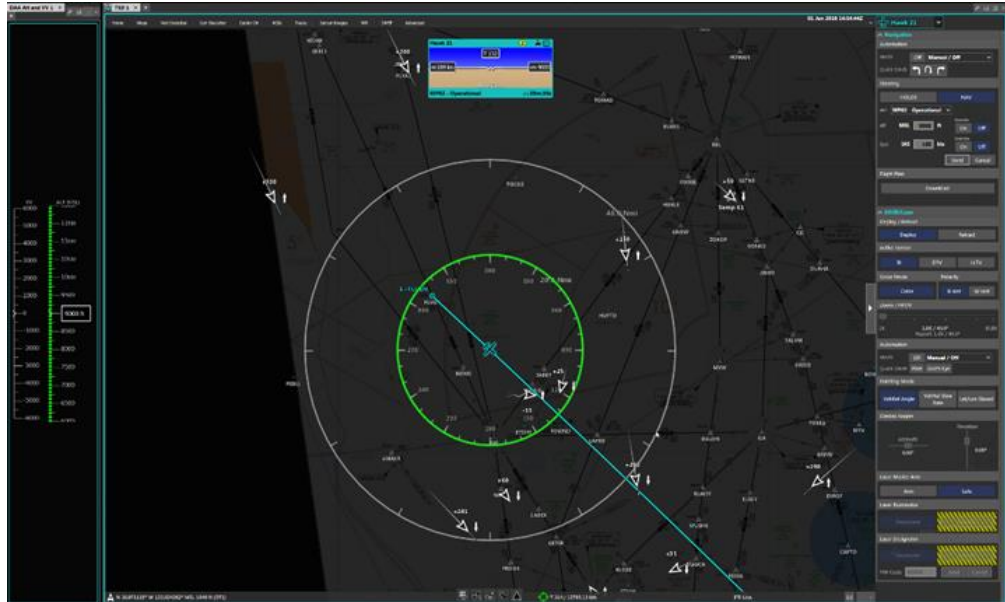
II. Method

A. Experimental Design

This study utilized a one-way, repeated measures design to analyze pilots' performance in maintaining DAA well clear across two different DAA display configurations (Integrated vs. Standalone). The purpose of the display location variable was to determine whether or not pilot performance was comparable between configurations when provided with the most current implementation of the Phase 1 DAA MOPS. While not designed to be tested statistically, it was also of interest to the authors to understand the effects of the intruder's threat type – whether the initial appearance of a threat was a corrective or warning alert - on pilots' performance.

1. Integrated

The Integrated display configuration provided pilots with DAA information within the GCS's primary display, the tactical situation display (TSD; see Figure 1). This allowed pilots to see DAA information, which included traffic location, DAA alerting and DAA maneuver guidance, alongside their routing information, airspace information and vehicle control interfaces. The traffic information made available to pilots (intruder location, range, bearing, heading, vertical trend, horizontal trend, and relative altitude) were implemented as defined by the DAA draft MOPS as the minimum traffic information requirements (at the time of data collection). The coupling of the TSD and DAA display allowed pilots to directly reference the vertical and horizontal maneuver guidance information as they were interacting with the vehicle controls. While maneuver guidance was always available for reference, there was no coupling of the guidance and vehicle controls, meaning pilots were free to disregard the guidance at their discretion. The monitor to the left of the TSD was left blank in this condition, leaving only two VSCS displays visible to the pilot: the TSD and health and status display.



2. Standalone

The Standalone display configuration removed all DAA information from the

Figure 1. Screenshot of TSD in the Integrated display configuration. The TSD contains DAA information alongside routing and airspace information. It also contains all vehicle control interfaces.

TSD and situated it within an adjacent display located to the left of the TSD (see Figure 2). The same DAA information that was available to pilots in the Integrated condition was visible in the Standalone condition – traffic information, DAA alerting and DAA maneuver guidance. The Standalone DAA display, however, contained no routing or airspace information and provided no vehicle control interfaces. Pilots could adjust the range and orientation of the Standalone display at any time, but were required to input any necessary changes to their aircraft on the TSD. Uploading changes to the vehicle worked identically between the two display conditions, and pilots were still able to disregard DAA guidance information at their discretion. All three VSCS displays were visible to the UAS pilot in this condition: Standalone DAA Display, TSD and health and status display.

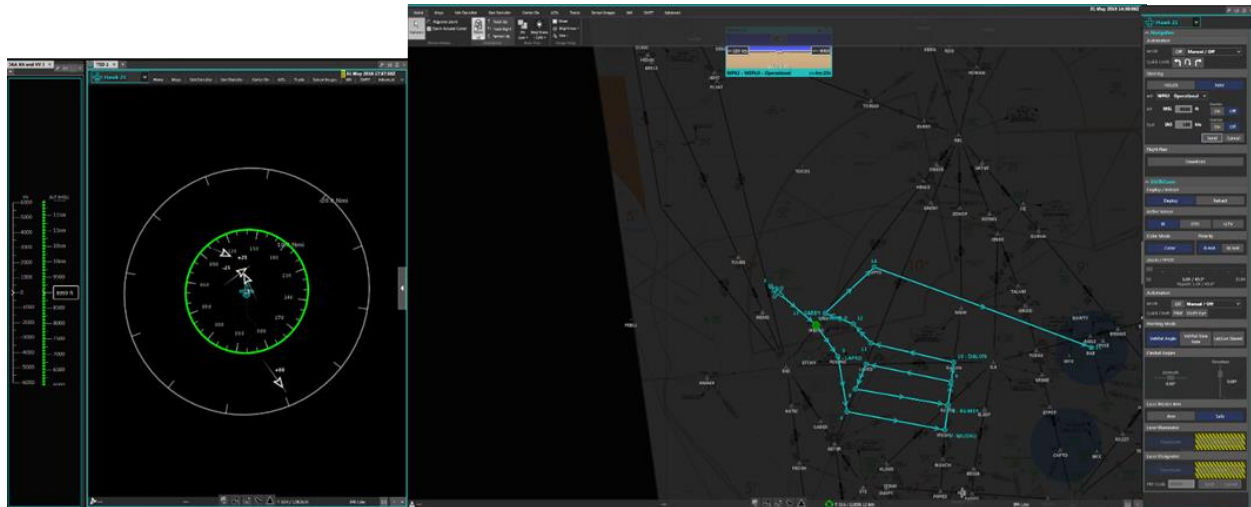


Figure 2. Screenshot of DAA display and TSD in the Standalone display configuration. The DAA display (left) contains all DAA-related information while the TSD (right) contains all routing and airspace information and vehicle control interfaces.

B. Participants

Sixteen active duty UAS pilots ($M = 30.5$ years of age) were recruited for this experiment. Two pilots participated per day, resulting in eight days of data collection. Participants averaged roughly 600 hours of UAS flying experience in military operations, and an average of 60 hours operating UAS in civil airspace. Two ATCs from the National Air Traffic Controllers Association (NATCA) participated as confederates in this experiment.

C. Simulation Environment

1. Ground Control Station

The Air Force Research Laboratory's Vigilant Spirit Control Station (VSCS)¹³ served as the experimental GCS. VSCS was configured to generate two or three different displays, dependent upon the experimental condition. At a minimum, VSCS consisted of the TSD and a right-side health and status display. The TSD served as the pilots' primary navigation and control display, containing the vehicle control interfaces as well as information pertaining to ownship (e.g., location, altitude, heading, routing) and the surrounding airspace (e.g., a low altitude map and navigation aids). During the Integrated display experimental condition, the TSD also provided DAA information (e.g., traffic information, DAA alerting and DAA guidance). The right-side health and status display included a chat client, aircraft status indicators (e.g. fuel remaining), and electronic checklists. A third display, a left-side monitor, was generated in the Standalone display experimental condition only (Figure 3). The third display depicted the same DAA information as provided by the TSD in the Integrated display condition but contained no routing information, airspace information or control interfaces.



Figure 3. VSCS in Standalone configuration. TSD, bottom-center display; health and status panel, right display; Standalone DAA display, left display.

The TSD's vehicle control interfaces allowed pilots to switch between two different navigation modes – "Navigation Mode" (NAV) and "Holds Mode" (HOLDS). NAV mode, the default level of control, supported waypoint-to-waypoint flying. The aircraft would follow their pre-defined routing without requiring interaction from the pilot. The pilot could, however, modify the assigned altitude for any pre-defined waypoint(s) on their route in order to upload a

desired altitude change to the aircraft while still flying waypoint-to-waypoint. Pilots also had the option to enter HOLDS mode, which provided pilots the ability to engage a heading, altitude and speed hold, where each value could be changed via keypad entry or the use of ‘spinners’ that would incrementally increase/decrease the heading, altitude or speed value. While in NAV mode, pilots also had the ability to modify their heading using a graphical heading bug tool that appeared on a compass rose surrounding ownship. Pilots, in this way, could directly compare their heading options to information on the TSD (such as DAA system information in the Integrated condition) rather than rely on a strictly numerical estimation. When pilots wanted to return to waypoint-to-waypoint flying, they would leave the HOLDS mode and re-enter NAV mode.

Two full VSCS configurations were built to allow two UAS to be flown simultaneously per experimental run. While they were run in parallel, UAS pilots were physically separated and unable to take control of the other station’s aircraft. Pilots interacted with all of the VSCS displays using standard mouse and keyboard inputs. They were able to adjust the display range of the TSD and Standalone DAA display (when available) from 5nm to a maximum range of 40nm. Pilots could also switch both displays, independently, between north-up and track-up orientations.

VSCS was also configured to run an additional traffic injection extension located on a remote display that was made available to researchers but not the pilot participants. This allowed researchers to manually launch tailored threats at a specific UAS in order to generate a subset of the conflicts required for the current study. While this tool was technically a part of the VSCS suite, it was invisible to the pilots of both UAS.

2. Experimental Airspace

The air traffic simulation environment utilized in this study was generated by the Multi-Aircraft Control Station (MACS) software suite¹⁶. MACS was configured to provide all simulated manned traffic (with the exception of traffic launched by the VSCS injection tool) within an experimental sector (Oakland Center ZOA 40/41), as well as generate a high-fidelity en route ATC display and two pseudo pilot stations. A confederate ATC managed all simulated manned and UAS traffic active within ZOA 40/41, while two pseudo pilots were trained to control all simulated manned traffic within the sector and to respond to ATC clearances as necessary. All experimental participants communicated over a common frequency using a push-to-talk headset.

3. Detect and Avoid System

The DAA system utilized in this study was the Java Architecture for DAA Modeling and Extensibility (JADEM)¹⁷, which has been used in each of the previous HITLs in this series of experiments. JADEM applied a prioritization logic to the traffic it received from MACS and VSCS within its simulated sensor ranges (within 15nm and $\pm 5000^\circ$), assigning alert levels to each traffic element based on its current or predicted proximity to ownship’s DAA well clear volume. DAA well clear was defined (in conjunction with RTCA SC-228¹³) as a horizontal miss distance (HMD) of 0.75nm, a vertical threshold (ZTHR) of 450ft, and a modified Tau (modTau) of 35sec. Traffic within, or predicted to

Table 2. DAA system alerting structure.

Alert Level	Separation Criteria	Time to Loss of DAA Well Clear	Icon	Aural Alert Verbiage	Expected Pilot Response
DAA Warning Alert	HMD = 0.75 nmi ZTHR = 450 ft. modTau = 35 sec	25 sec		“Traffic, Maneuver Now; Traffic, Maneuver Now”	Maneuver immediately
Corrective DAA Alert	HMD = 0.75 nmi ZTHR = 450 ft. modTau = 35 sec	55 sec		“Traffic, Avoid”	Maneuver following ATC approval
Preventive DAA Alert	HMD = 0.75-1.0 nmi ZTHR = 450-700 ft. modTau = 35 sec	N/A		“Traffic, Monitor”	Monitor traffic; maneuver not currently required
Guidance Traffic Alert	Associated with banding outside current course	N/A		N/A	No maneuver required
None (Target)	Within surveillance field of regard	N/A		N/A	No maneuver required

enter, this threshold received distinct aural and visual alerts (see Table 2 for the various alert types). The predicted future states of both intruders and ownship were extrapolated using an assumption of constant velocity.

In addition to assigning alert levels to all traffic within range of the UAS, JADEM also provided suggestive maneuver guidance in the form of ‘banding’. Banding refers to color-coding markings on the DAA display that explicitly indicate which trajectory options (namely headings and altitudes) are predicted to lead to corrective or warning alerts, and those that are not (Figure 4). Heading and altitude values that are predicted to maintain well clear are color-coded green, while those that are predicted to lead to a corrective or warning alert are color-coded yellow or red, respectively. Vertical maneuver guidance (i.e., altitude bands) was located on an altitude tape positioned on the left of the DAA display (the immediate left of the TSD in the Integrated condition and on the left side of the monitor in the Standalone condition) with a range of $\pm 3000'$ of ownship’s current altitude. Horizontal maneuver guidance (i.e., heading bands) was located on the inner range ring and covered all 360° around ownship. The DAA banding was continuously updated to provide pilots with a constant snapshot of their surrounding airspace. In the case of multiple intruders, the bands were additive, with warning alerts always receiving priority in the color-coding scheme.

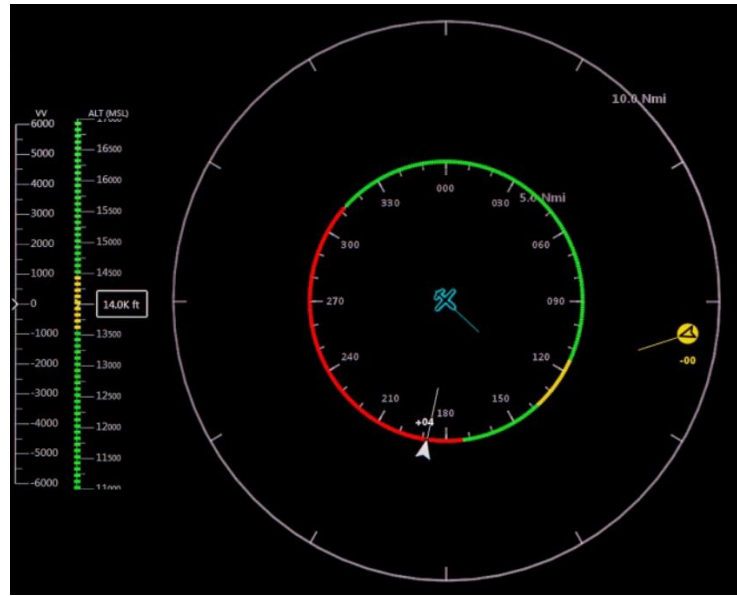


Figure 4. Screenshot of vertical and horizontal DAA maneuver guidance on the VSCS Standalone DAA display. Green bands indicate trajectories (headings and altitudes) predicted to be conflict free, while yellow and red trajectories are predicted to lead to either corrective (yellow) or warning (red) alerts.



Figure 5. Screenshot of vertical and horizontal DAA maneuver guidance to regain well clear on the VSCS Standalone DAA display. The typical heading and altitude bands are fully saturated red. The two green ‘wedges’ indicate the heading and altitude options that will maximize separation with the offending aircraft.

While vertical and horizontal guidance is provided to pilots with the intent to support their ability to maintain DAA well clear, in some instances (e.g., last-second acceleration by an intruder in the direction of ownship) a loss of DAA well clear cannot be avoided. When that occurs, the design of the DAA banding causes all vertical and horizontal guidance to become ‘saturated’ with red, indicating that all possible trajectories lead to at least a warning alert and a predicted loss of well clear. This saturation becomes problematic because there is no positive guidance provided to the pilot. To accommodate this limitation, JADEM also generated DAA well clear recovery guidance to assist pilots in re-establishing well clear. Recovery guidance was indicated by a green “wedge” that highlighted a range of recommended headings or altitudes that would maximize separation at closest point of approach (Figure 5). The DAA well clear recovery guidance did not replace the concurrent red banding, but served to emphasize the pilot’s best course of action until well clear was regained.

D. Procedure

1. Training

Participants completed two forms to start the day - an informed consent form and a brief demographics form. The demographics form asked questions related to the pilots' previous experience in unmanned and manned aviation. Following an initial briefing covering experimental procedures, three different training sessions were administered separately to each of the days' two participants. The first training session focused on the basic functionality of VSCS, which included topics such as how to interact with the TSD's vehicle control interfaces, complete the electronic checklists, and respond to the chat client. Once comfortable flying the UAS and performing other basic functions, participants received their second training session on whichever display condition they were to receive first according to the experimental protocol (Integrated or Standalone). The display-dependent training covered the pilot's role in the DAA task, outlining the traffic information, alerting and maneuver guidance provided by the DAA system. Pilots were trained explicitly on how they were expected to react to each alert level (see Table 2). A hands-on demonstration of the DAA functionality was followed by a 20-minute practice mission using the display configuration under test. During the practice scenario pilots were required to resolve several scripted conflicts and coordinate, where necessary, with ATC. Researchers monitored pilots during the practice session to verify that they understood how to appropriately respond to the DAA system alerts and that they were aware of the maneuver guidance features. Two experimental trials followed the completion of this portion of the training. The second half of the day began with the third training session (this time on the display condition that the pilot had not yet seen), followed by another 20-minute practice scenario. Pilots then completed their final two experimental trials.

2. Pilot Task

Pilots operated two different simulated MQ-9 Reapers over the course of the study, "HAWK21" and "SAMP61", along dedicated mission routing. Both simulated UAS flew within Oakland Center airspace (ZOA 40/41) under instrument flight rules (IFR). The two UAS were in the same airspace and were visible to each other but could only be controlled by their respective GCS. (There were no scripted conflicts between the two UAS along their flight paths.) Pilots' primary responsibility was navigating their UAS along their mission track while remaining DAA well clear of scripted encounters. Pilots received alerts when an intruder was predicted to lose DAA well clear with ownship according to the DAA well clear criteria. When pilots received a corrective DAA alert they were expected to coordinate their eventual maneuver with ATC, where they were expected to maneuver immediately against warning alerts. In both cases, pilots were expected to determine the resolution on their own, rather than request a clearance from ATC. Once a threat had been resolved, pilots were then responsible for coordinating their return to their pre-approved mission routing with ATC as soon as practical.

Pilots were also responsible for managing a variety of scripted health and status tasks. These secondary tasks included monitoring and responding to prompts from a chat window for aircraft status information (e.g., "what is your current fuel remaining in lbs.?") and completing electronic checklists in response to simulated system failures.

3. Scenarios

For the purpose of this experiment two different mission routes were developed, "Fire Line Track" and "Air Sampling Track." In the Fire Line Track, flown by HAWK21, the UAS served as an air asset for the California Department of Forestry, monitoring a fire burning north of Clear Lake in Lake County, CA. The track started with HAWK21 at 9,000' and included a climb to 14,000' on the last leg of the track. The Air Sampling Track, flown by SAMP61, had the UAS serve as an air asset for the California Air Resources Board to measure air quality east of Santa Rosa, CA. The track started at 10,000' and then had the pilot climb to 14,000' before eventually returning to 10,000'. Each GCS and associated mission route was flown once per display configuration.

Manned traffic scenarios were created by an ATC subject matter expert simulating real sector activity in Oakland center, ZOA 40/41. The scenarios were designed to provide equivalent workload for the pilot. There were six intruders scripted to lose DAA well clear (i.e., generate a corrective or warning alert) with ownship in each traffic scenario. The encounters were designed to address the major functional areas of DAA. This included a mix of the following encounter types, spread across the two traffic scenarios: intruder and ownship level, high-speed intruder, multi-threat, intruder and/or ownship in climb/descent, and late-acceleration (i.e., the intruder registers first as a warning, rather than the typical corrective alert). The encounters were also scripted to vary in approach angle and relative speed.

4. Experimental Trials

Each participant completed four 60-minute experimental trials across the two display configurations (Integrated and Standalone) and mission scenarios (Fire Line Track and Air Sampling Track). Experimental trials were blocked by display configuration, which was counterbalanced across participants and mission scenarios to account for learning and order effects. After each experimental block participants completed a subjective questionnaire and the NASA Task Load Index (TLX)¹⁸. A post-simulation questionnaire was administered to participants at the conclusion of the final experimental trial followed by a verbal debrief.

III. MEASURES

This paper reports on two different aspects of pilot responses to DAA display alerts: measured response and loss of DAA well clear. The measured response metrics were extracted from a pilot-DAA interaction timeline that consisted of six stages in the pilots' response to a DAA alert (see Table 1). In the DAA timeline, encounters started at the onset of a corrective or warning alert (T_0) and ended when the pilot uploaded their final maneuver to the aircraft (T_{4b}). Output generated by JADEM, VSCS, and audio/video recordings were used to capture the times for each stage of the pilot-DAA interaction timeline (e.g., pilot notifies ATC, pilot begins interaction with vehicle control interface). Once the interaction timeline was completed for a given encounter, response times could be extracted across any two stages. While any number of metrics can be derived from the resulting timeline, the metrics reported here focus on how quickly the pilot could get "in-the-loop" and implement a traffic avoidance maneuver. In addition to measured response, three different aspects of loss of DAA well clear are reported, generated using JADEM output logs as well as reviews of video recordings. The metrics provide insight into pilots' ability to maintain safe separation from scripted conflicts across the two display configurations.

Initial Response Time ($T_3 - T_0$). A measure of the time it takes a pilot to initiate an input (i.e., edit) into one of the vehicle control interfaces. It is the difference between the first appearance of the alert and the start of the relevant edit.

Initial Edit Time ($T_{4a} - T_3$). A measure of the time it takes a pilot to implement an initial edit into one of the vehicle control interfaces. It is the time between the start of the relevant edit and the first upload to the aircraft. This metric is only relevant if a pilot made multiple uploads to the aircraft; when pilots made only one upload, initial edit time is equivalent to total edit time.

Total Edit Time ($T_{4b} - T_3$). A measure of the time it takes a pilot to complete all edits into the vehicle control interfaces. It is the time between the start of the relevant edit and the final upload to the aircraft.

Aircraft Response Time ($T_{4a} - T_0$). A measure of the time from the onset of a DAA alert to the time the pilot sends the first maneuver command to the aircraft in response to a traffic alert (i.e., initial response time + initial edit time). It is the time between the initial appearance of the traffic alert and the first upload to the aircraft.

Total Response Time ($T_{4b} - T_0$). A measure of the time it takes a pilot to upload a final maneuver command to the aircraft in response to a traffic alert (i.e., initial response time + total edit time). It is the time between the initial appearance of the traffic alert and the final upload to the aircraft.

Loss of DAA Well Clear Proportion. The proportion of encounters where pilots failed to maintain the DAA well clear separation standard out of all threats predicted to lose DAA well clear, as detected by the DAA system. Only threats that provided the pilot with sufficient time to resolve the conflict ($>15s$) are included in this metric.

Loss of DAA Well Clear Categorization. A diagnosis of the loss of DAA well clear. Three different types of loss of DAA well clear were identified: 1) ineffective maneuver (pilot had sufficient time [$>15s$] to resolve the conflict but the resolution maneuver failed to eliminate threat), 2) too slow (pilot had sufficient time to resolve the conflict but failed to upload a resolution to the aircraft in time), and 3) mismatch between display orientations (DAA display and TSD were in conflicting orientations [north-up vs. track-up], negatively impacting pilot's ability to select appropriate maneuver). Category three was only possible in the Standalone condition.

Loss of DAA Well Clear Severity. The physical extent to which an intruder penetrated the DAA well clear volume. Expressed as a percentage such that a larger percentage equates to greater penetration of the separation threshold. See Phase 1 DAA MOPS Appendix L¹⁰ for details on severity metric.

IV. RESULTS

The first six metrics listed above were analyzed across the two display configurations (Integrated and Standalone) utilizing a paired samples t-test. An alpha level of .05 was used for these analyses. Descriptive statistics were generated for the response time metrics as a function of display configuration and threat type (i.e., corrective or warning at first alert). Statistical tests were not performed with respect to the threat type variable due to uneven sample sizes (corrective at first alert, $N=436$; warning at first alert, $N=30$). Descriptive statistics were also generated for the loss of DAA well clear categorization and loss of DAA well clear severity metrics.

A. Initial Response Time

Pilots' initial response times were found to differ significantly between display configurations, $t(15) = 3.151$, $p < .01$. Initial response times were faster with the Integrated display ($M = 9.35s$; $SE = 0.54s$) compared to the Standalone display ($M = 10.75s$; $SE = 0.56s$). Figure 6 shows pilots' initial response times as a function of display configuration and threat type at first alert.

B. Initial Edit Time

No significant effect of display configuration was found on pilot's initial edit times, $t(15) = -3.41$, $p > .05$. Figure 7 shows pilots' initial edit times as a function of display configuration and threat type at first alert.

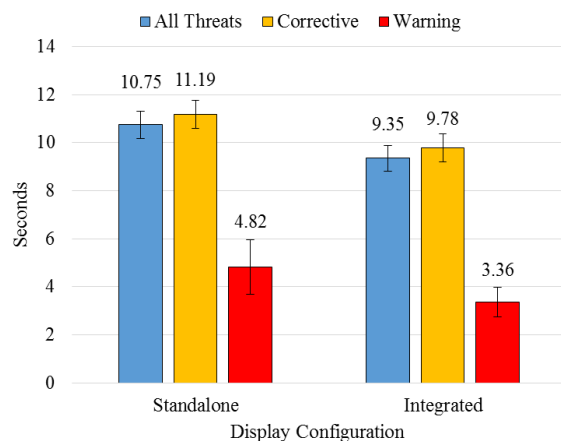


Figure 6. Mean initial response time (and SE) by display configuration and threat type.

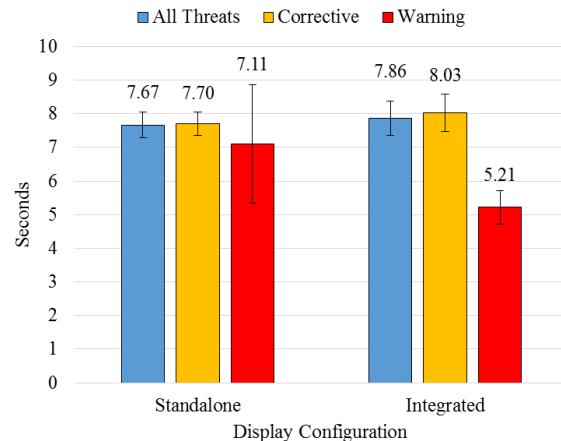


Figure 7. Mean initial edit time (and SE) by display configuration and threat type.

C. Total Edit Time

No significant effect of display configuration was found on pilots' total edit times, $t(15) = .787$, $p > .05$. Figure 8 shows pilots' total edit times as a function of display configuration and threat type at first alert.

D. Aircraft Response Time

Pilots' aircraft response times were found to differ significantly between display configurations, $t(15) = 2.355$, $p = .033$. Aircraft response times were faster with the Integrated display ($M = 17.08s$; $SE = 0.59s$) compared to the Standalone display ($M = 18.37s$; $SE = 0.62s$). Fig. 9 shows pilots' aircraft response times as a function of display configuration and threat type at first alert.

E. Total Response Time

Pilots' total response times were also found to differ between display configurations, $t(15) = 3.007$, $p < .01$. Total response times were significantly faster with the Integrated display ($M = 18.25s$; $SE = 0.59s$) compared to the Standalone display ($M = 20.25s$; $SE = 0.71s$). Fig. 10 shows pilots' total response times as a function of display configuration and threat type at first alert.

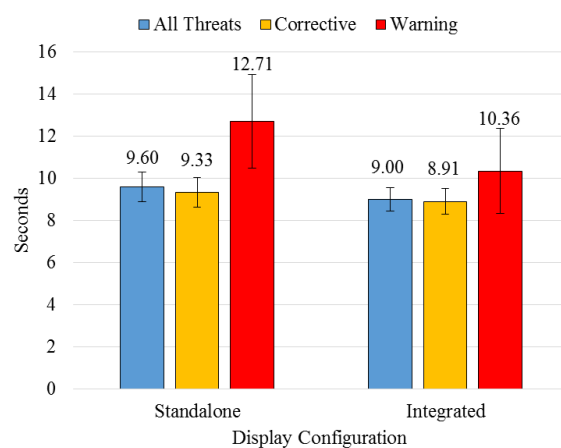


Figure 8. Mean total edit time (and SE) by display configuration and threat.

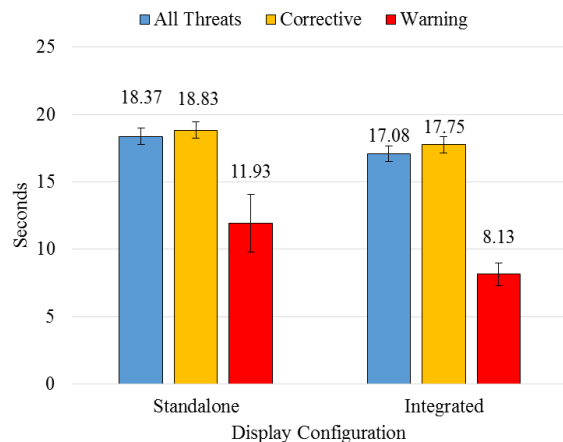


Figure 9. Mean aircraft response time (and SE) by display configuration and threat type.

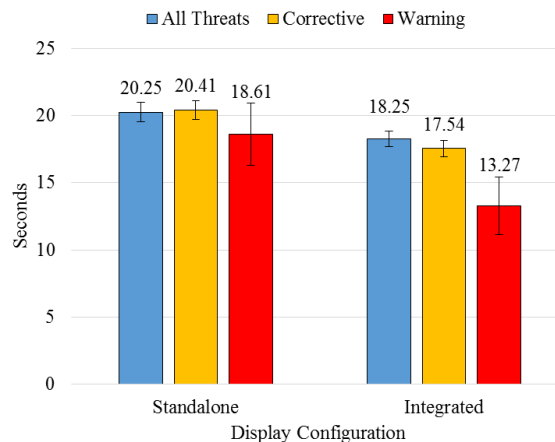


Figure 10. Mean total response time (and SE) by display configuration and threat type.

F. Loss of DAA Well Clear Proportion

Display configuration did not have a significant effect on the proportion of encounters that resulted in a loss of DAA well clear (LoDWC), $t(15) = 1.227$, $p > .05$ (Fig. 11). Pilots were found to be at fault for a loss of DAA well clear an average of 3% of the time in the Standalone condition (a total of 7 times out of 234 encounters), compared to an average of 1% of the time in the Integrated condition (a total of 3 times out of 232 encounters). Figure 9 shows the proportion of all LoDWC (not just those for which the pilot was at fault) as a function of the time to loss of DAA well clear at first alert (i.e., the time pilots had available to resolve the threat when it was first detected by the DAA system). As shown in the figure, the proportion of LoDWC decreased as the time to LoDWC at first alert increased. When pilots had more than 20s to LoDWC, they lost well clear 3% of the time (15 instances out of 435), compared to 57% of the time (8 out of 14) when they had less than 20s.

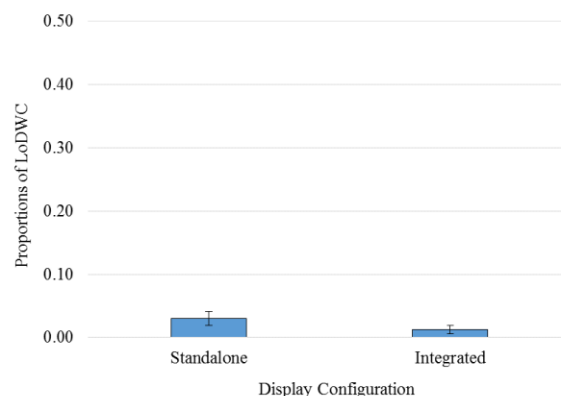


Figure 10. Proportion of losses of DAA well clear (LoDWC) by display configuration.

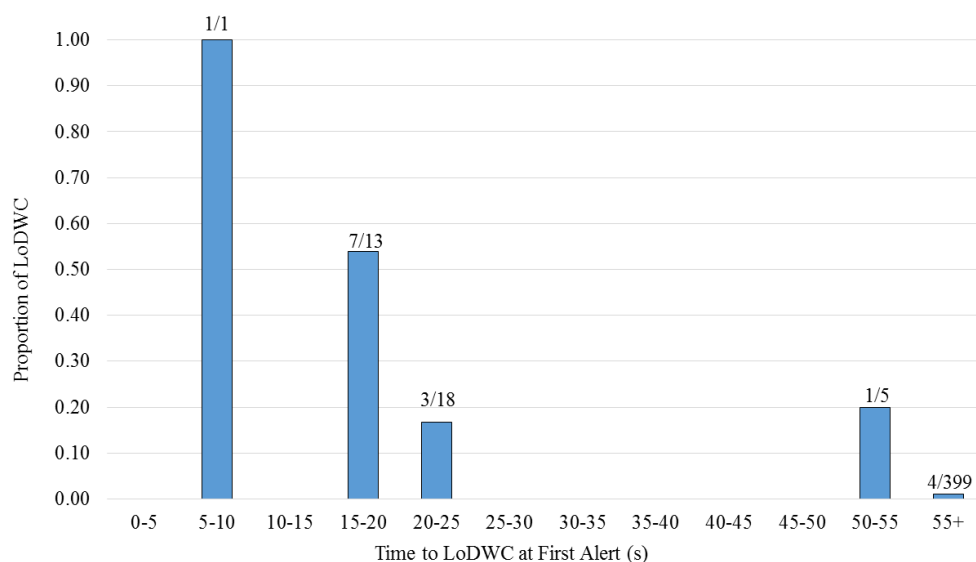


Figure 9. Proportion of losses of DAA well clear (LoDWC) by time to loss of DAA well clear at first alert.

G. Loss of DAA Well Clear Categorization

There were a total of 16 LoDWC throughout the experiment, six of which occurred with less than 15s time to loss of well clear at first alert. Those six LoDWC were by default not counted against pilots since there was insufficient time to notice the alert, determine an appropriate response and provide the aircraft with time to maneuver (based on pilot response time results from the previous HITLs, namely Rorie, Fern and Shively⁶). Of the remaining ten LoDWC, each instance was reviewed in order to assess the cause of the loss of DAA well clear. As shown in Table 3, five of seven LoDWC in the Standalone condition, and all three of the LoDWC in the Integrated condition, were due to pilots uploading an ineffective maneuver to the aircraft, despite the availability of viable maneuver options at the time of the upload. Of the remaining two LoDWC in the Standalone condition, one was due to the pilot waiting too long to initiate a maneuver against a threat and the other resulted when the pilot struggled to implement a maneuver when the TSD and Standalone DAA display were in different orientations (the TSD was north up, while the DAA display was track up).

Table 3. Loss of DAA Well Clear Categorization by DAA Display Configuration

Display Configuration	Count of LoDWC Category
Standalone	(5) Ineffective Maneuver (1) Too Slow (1) Mismatch between display orientations
Integrated	(3) Ineffective maneuver

H. Loss of DAA Well Clear Severity

All 16 LoDWC were analyzed according to their severity (i.e., the percentage that the DAA well clear volume was penetrated, with larger percentages associated with greater violation). While statistical analyses were not performed due to many pilots lacking instances of LoDWC in both display conditions, losses of DAA well clear in the Integrated condition (5.45%) were, on average, slightly less severe than those in the Standalone condition (8.76%). Pilots were thus able to keep intruders within the outer 10% of the DAA well clear volume in both display configurations.

V. DISCUSSION

The purpose of the current study was to validate the recently-defined minimum information requirements for pilots performing the DAA traffic avoidance function. Pilots were provided with identical DAA information presented in two different locations in the GCS: integrated with the primary navigation display (TSD) or situated as a standalone display to the left of the TSD. In addition to standard traffic information, the DAA display included suggestive maneuver guidance ('banding') to assist pilots in selecting safe trajectories around predicted threats to DAA well clear. The effect of display location was analyzed with respect to pilots' measured response times and their ability to maintain DAA well clear from scripted conflicts. The effect of threat type on pilots' response times was also reported. Finally, comparisons are made to the most recent DAA HITL (Rorie, Fern and Shively⁶) in an attempt to determine how comparable pilot performance is between the studies.

A. Measured Response

1. Effect of Display Location

Display location was found to have a moderate effect on pilot response times. Even in cases where it had a significant main effect (initial response time, aircraft response time & total response time), the differences between the two conditions were within 2 seconds. In all three instances of a significant main effect of display location, the integrated display condition was associated with shorter response times.

Initial response times, a measure of the time from the onset of a corrective or warning DAA alert to the pilots' first interaction with the vehicle control interfaces, were 1.4s faster when the DAA information was collocated with the TSD compared to when the DAA information was on a standalone display (9.35s versus 10.75s). This reduction in response time is likely a result of pilots not having to divide their attention between a standalone display with traffic information and their primary navigation display when determining an appropriate resolution maneuver away from the traffic conflict. The small difference in initial response times between the two display configurations may in part be due to the amount of time it took in general for pilots to initiate their responses to detected conflicts. Pilots, on average, spent the 10 seconds immediately following the appearance of an alert determining their desired response and coordinating their maneuver with ATC. This relatively slow response time indicates a general lack of urgency that likely mitigated any potential stronger effects of DAA display location. As shown in Table 4, the initial response

times observed in the current study roughly align with the fastest initial response times seen in Rorie, Fern and Shively⁶ [9.32sec (No Fly Bands display)].

Initial and total edit times - measures of the time pilots spent interacting with the vehicle control interfaces before uploading their first, then final, change to the aircraft - were not found to differ significantly by display location. Each metric differed by less than one second between conditions, suggesting that pilots had largely determined their desired maneuver by the time they began interacting with the control interfaces. This allowed pilots to focus on switching navigation modes and uploading a desired heading or altitude change to the aircraft, functions that were performed within the TSD and were functionally identical between display conditions. Initial edit times in the current study (Standalone display = 7.67s; Integrated display = 7.86s) were about one second faster than they were for the No Fly Bands and Omni Bands displays (8.42s and 8.78s, respectively) in Rorie, Fern and Shively⁶ (Table 4). The total response times between the current study and the two banding displays in Rorie, Fern and Shively were virtually identical, ranging from 9.00s to 9.61s.

Table 4. Response time metrics (in sec) from from the current study and Rorie, Fern and Shively⁶, by display configuration.

	Current Study		Rorie, Fern and Shively ⁶			
	Standalone Display	Integrated Display	Information Only	No Fly Bands	Omni Bands	Vector Planner
Initial Response Time	10.75	9.35	12.45	9.32	11.28	16.35
Initial Edit Time	7.67	7.86	9.06	8.42	8.78	6.33
Total Edit Time	9.60	9.00	14.72	9.46	9.61	8.12
Aircraft Response Time	18.37	17.08	21.39	17.74	20.06	22.68
Total Response Time	20.25	18.25	27.05	18.78	20.90	24.47

The aircraft response time and total response time metrics were the addition of initial response time to initial and total edit times, respectively. Display location, as with initial response time, was found to have a significant main effect on both metrics. As seen, however, the source of this difference is faster pilot initial response times in the integrated condition, as compared to the standalone condition, rather than a result of any difference in pilots' edit times. Integrating the DAA information into the TSD corresponded to a 1.29s reduction in aircraft response times (17.08s versus 18.37s) and a 2s reduction in their total edit times (18.25s versus 20.25s). The aircraft and total response times recorded in the current experiment corresponded roughly to the fastest such times seen in Rorie, Fern and Shively⁶ [17.74s (No Fly Bands, aircraft response time) & 18.78s (No Fly Bands, total response time)].

2. Effect of Threat Type

While statistical analyses could not be performed on the measured response metrics as a function of threat type due to highly unequal sample sizes, it was possible to look at trends from the descriptive statistics. This was deemed necessary since alert type can be expected to have a major effect on response times; pilots were instructed to coordinate their maneuver with ATC in response to corrective alerts, but told to not coordinate their maneuver in response to a warning alert (i.e., maneuver immediately). As expected, pilots were generally faster in responding to warning alerts than they were to corrective alerts, an indication that pilots understood the limited amount of time they had when responding to warning alerts. There were several areas in particular, however, that did not conform to expectations: initial edit times, total edit times and total response times. In all cases, the effect of threat type on pilot responses was smaller, or reversed, than been seen previously. Table 5 shows the response time metrics from the current experiment by display configuration and threat type compared to the same metrics for the Omni Bands display from Rorie, Fern and Shively⁶. The Omni Bands display used the same DAA system and provided pilots with identical maneuver guidance as was made available in the current study, making it the most direct comparison possible between experiments.

When broken down by display configuration and alert type, initial response times drop substantially from corrective to warning alerts in both the integrated and standalone displays. Initial response times to warning alerts dropped 6.37s in the standalone condition (4.82s versus 11.19s), while they dropped 6.42s for the integrated display condition (3.36s versus 9.78s), indicating that pilots started their maneuver away from a declared threat far quicker when it appeared first as a warning, rather than corrective, alert. When compared to Rorie, Fern and Shively⁶ (shown in Table 5), initial response times to warning alerts were comparable between studies, with responses in both

experiments falling within five seconds. Initial response times to corrective alerts, however, dropped in the present study, both in the integrated condition and the standalone condition. The integrated display was 3.57s faster than the Omni Bands display in Rorie, Fern and Shively in response to corrective alerts (9.78s versus 13.53s), while the standalone display was 2.34s faster than the Omni Bands display (11.19s versus 13.53s).

The inclusion of alert type when looking at initial edit times shows a markedly smaller effect than seen for initial response times. Initial edit times when pilots were responding to warning alerts relative to corrective alerts dropped only 0.56s in the standalone display condition (7.11s versus 7.70s) while dropping 2.82s in the integrated condition (5.21s versus 8.03s). Both of these reductions in response times are smaller than those seen in initial response times, which were both more than six seconds. When looking instead at the effect of display location within each individual alert level, you see another new trend. Whereas the improvement seen for initial response times in the standalone condition was equivalent for both corrective and warning alerts (reducing initial response times by 1.5s for both threat types), initial edit times actually slightly increased in the integrated condition compared to the standalone condition when pilots were responding to corrective alerts (8.03s versus 7.70s), a reversal of the trends seen thus far. When looking at warning alerts, however, the previous trend held – pilots were faster (albeit only 1.9s) in the integrated condition compared to the standalone condition (5.21s versus 7.11s).

Initial edit times in response to corrective alerts in the current study were a little over a second faster than those seen in the Omni Bands display (7.70s & 8.03s versus 9.23s) in Rorie, Fern and Shively⁶ (Table 5). The integrated display in the current study also resulted in slightly faster initial edit times to warning alerts than those seen in Rorie, Fern and Shively (5.21s versus 6.05s). The standalone display, however, was seen to result in initial edit times that were just over a second longer in response to warning alerts than seen in the earlier experiment (7.11 versus 6.05s). This may be, in part, due to the difficulty of implementing a change to the aircraft when the control interfaces are separate from the traffic information and the pilot is responding with urgency to a high-priority alert. Regardless, the differences in initial edit times between simulations were minor and, more often than not, faster in the current study.

Total edit times also challenged expectations when alert type was added to the comparison. When both alert type and display location are included, pilots' total edit times were longer in response to warning alerts than they were to corrective alerts for both the standalone and integrated conditions. Pilots' total edit times to warning alerts were 3.38s longer than to corrective alerts in the standalone condition (12.71s versus 9.33s) and 1.45s longer in the integrated condition (10.36s versus 8.91s), a noteworthy reversal to the trend seen in the other metrics and in previous studies. The other trend, which had the integrated display resulting in faster response times than the standalone display, still held here across alert levels, albeit more pronounced in the case of warning alerts. When looking only at corrective alerts, the integrated display only reduced total edit times by 0.42s compared to the standalone display (8.91s versus 9.33s), whereas the integrated display reduced total edit times by 2.35s compared to the standalone display (10.36s versus 12.71s) when looking only at warning alerts.

Comparing total edit times between the current study and Rorie, Fern and Shively⁶, pilots were seen responding almost identically to corrective alerts, but more slowly to warning alerts (Table 5). Total edit times in response to corrective alerts were roughly nine seconds across both simulations. Pilots, however, spent more time finishing their edits in the current study when responding to warning alerts than pilots did in Rorie, Fern and Shively (12.71s & 10.36s versus 8.86s). The most likely cause of this difference is the inclusion of guidance to regain DAA well clear in the

Table 5. Response time metrics (in sec) from the current study and the Omni Bands display from Rorie, Fern and Shively⁶, by display configuration and threat type. (Authors reanalyzed response time data in Rorie, Fern and Shively in order to account for threat type variable.)

Metric	Standalone Display		Integrated Display		Omni Band Display (Rorie, Fern and Shively ⁶)	
	Corrective	Warning	Corrective	Warning	Corrective	Warning
Initial Response Time	11.19	4.82	9.78	3.36	13.53	4.38
Initial Edit Time	7.70	7.11	8.03	5.21	9.23	6.05
Total Edit Time	9.33	12.71	8.91	10.36	9.33	8.86
Aircraft Response Time	18.83	11.93	17.75	8.13	22.75	10.43
Total Response Time	20.41	18.61	17.54	13.27	22.86	13.24

current study. (It should be noted that guidance to regain DAA well clear was available to pilots in the No Fly Bands condition in Rorie, Fern and Shively, but not to pilots in the Omni Bands display.) As described above, guidance to regain DAA well clear came into effect late in an encounter when a loss of DAA well clear could no longer be avoided. Pilots were instructed to comply with this guidance, even when they had already maneuvered in an initial attempt to avoid the loss of DAA well clear. This meant that pilots responding to warning alerts, which by definition are closer to the DAA well clear boundary than are corrective alerts when first alerted, were often required to make additional uploads late into the encounter to comply with the DAA well clear recovery guidance. Since total edit times include the final upload to the aircraft, as opposed to initial edit times which only include the first upload to the aircraft, guidance to regain DAA well clear inflated total edit times without affecting initial edit times.

The effect of alert type on initial and total edit times is reflected in the aircraft and total response times. Whereas the presence of guidance to regain DAA well clear inflated total response times in response to warning alerts, it had no such effect on aircraft response times, which followed the expected trends. Aircraft response times to warning alerts dropped 6.9s in the standalone condition relative to corrective alerts (11.93s versus 18.83s) and 9.62s in the integrated condition relative to corrective alerts (8.13s versus 17.75s). When looking, instead, at the effect of the display location within each alert level, you see the standalone configuration having a stronger effect in response to warning alerts than to corrective alerts. When responding to warning alerts only, aircraft response times were 3.8s shorter in the integrated condition than they were in the standalone condition (8.13s versus 11.93s). Aircraft response times in response to corrective alerts, conversely, dropped only 1.08s in favor of the integrated condition compared to the standalone condition (17.75s versus 18.83s).

Compared to Rorie, Fern and Shively⁶, aircraft response times to corrective alerts were several seconds faster in the current study, (18.83s & 17.75s versus 22.75s). Aircraft response times were also faster (2.3s) in the current study when pilots were responding to warning alerts in the integrated condition (8.13s versus 10.43s). This trend was not seen for pilots responding to warning alerts in the standalone condition, however, which led to slightly longer aircraft response times (1.5s) than had been seen earlier (11.93s versus 10.43s).

As noted, the presence of guidance to regain DAA well clear impacted the effect of alert type on total response times. Total response times in the standalone display condition reduced only 1.8s when pilots were responding to warning alerts rather than corrective alerts (18.61s versus 20.41s). In the integrated condition, total response times dropped 4.27s in response to warning alerts when compared to corrective alerts (13.27s versus 17.54s). Once again, the integrated display resulted in slightly faster responses to warning alerts, reducing total response times by 5.34s, compared to the standalone display (13.27s versus 18.61s). Total response times, however, only dropped by 2.87s in the integrated condition compared to the standalone display (17.54s versus 20.41s) when pilots were responding to corrective alerts.

By comparison, pilot responses to warning alerts in the Omni Bands condition in Rorie, Fern and Shively⁶ were 9.62s shorter than when pilots in that study responded to corrective alerts (13.24s versus 22.86s). As discussed above, the muted effect of alert type in the present experiment on total response times is due to the additional late maneuvers made by pilots in compliance with guidance to regain DAA well clear. Despite this, pilots in the integrated condition were still able to produce identical total response times when responding to warning alerts to those seen in Rorie, Fern and Shively. Total response times for the standalone display, however, were 5.37s slower in the current study than the earlier experiment (18.61s versus 13.24s). When responding to corrective alerts, however, pilots were faster in both display conditions in the current study than they were in Rorie, Fern and Shively (20.41s & 17.54s versus 22.86s).

B. Loss of Well Clear

The effect of display location was even smaller for the loss of DAA well clear data than the response time data. While the Standalone display did result in a slightly higher proportion of LoDWC where the pilot was at fault (3% vs. 1% of predicted threats to DAA well clear), the difference was a matter of only four losses of DAA well clear out of several hundred encounters per display. When compared to Fern¹⁹ (Table 6), which reported the loss of DAA well clear data from the Rorie, Fern and Shively⁶ experiment, the two display conditions in the current experiment match up favorably. With the exception of the Omni Bands display in Fern¹⁹ (which resulted in 0 losses of DAA

Table 6. Proportion of LoDWC from from the current study and Fern¹⁹, by display configuration.

	Display Configuration	Proportion of LoDWC
Current Study	Standalone Display	.03
	Integrated Display	.01
Fern ¹⁹	Information Only	.09
	No Fly Bands	.03
	Omni Bands	.00
	Vector Planner	.04

well clear in which the pilot was deemed at fault), the displays in the current experiment matched or outperformed those in the earlier study.

Display location also failed to result in any substantial effect on LoDWC severity. While the severity of LoDWC trended in favor of the Integrated display condition, both configurations resulted in minimally severe separation violations (both were under 10%). This is despite the fact that most LoDWC occurred when pilots had less than 20s to a loss of DAA well clear. When pilots had little time to respond, LoDWC proportions unsurprisingly exceeded 50%. Conversely, when pilots had more than 20s to respond, that number dropped to 3%. What the severity metric shows, however, is that even when a loss of DAA well clear could not be avoided, the display features available to pilots in this experiment (including guidance to both maintain and regain DAA well clear) allowed them to minimize the extent that the DAA well clear boundary was penetrated. Unfortunately, the LoDWC severity metric used in this study was not used in Fern¹⁹, so a comparison between studies is not possible.

When classifying instances of a loss of DAA well clear, a common result was a lack of time provided to the pilot, making it all but impossible to make the necessary changes to the aircraft in time. As mentioned, one of the encounter types included in the experimental design was a late-accelerating intruder, designed to stress the DAA system and test the display of guidance to regain DAA well clear. It was this specific intruder, more than anything else, that accounted for losses of DAA well clear. There were, however, other reasons that pilots lost DAA well clear. The standalone display condition and the integrated display condition both experienced losses of DAA well clear as a result of an ineffective maneuver (despite having a minimum of 15s to loss of DAA well clear at first alert). The standalone condition had five such loss of DAA well clear types, while the integrated condition had three. This happened most often in both display conditions when pilots made a vertical maneuver without first ensuring that the new target altitude would be conflict-free. Two factors likely contributed to these cases. First, the vertical DAA maneuver guidance (i.e., altitude bands) were to the periphery of the DAA display, meaning it may have fell slightly out of pilots' scan pattern as they were reacting to active threats. This would explain why pilots made maneuvers in that dimension despite the availability of vertical maneuver guidance indicating that the proposed trajectory was unsafe. Second, the simulated UAV's climb/descent rate was fixed at 1000' per minute. This limited vertical rate meant that the window available to pilots to resolve a threat in the vertical dimension closed more quickly than did the window in the horizontal dimension (the vehicle's simulated turn rate was 5° per second). Together, these causes accounted for the majority of ineffective maneuvers.

The Standalone display also had two other types of losses of DAA well clear. One of these instances occurred when a pilot spent too much time interacting with the vehicle control interfaces, preventing them from sending a maneuver to the aircraft before separation was lost. This may partially be explained by the fact that the DAA display and the TSD were physically separated, making it harder to incorporate the desired change. Finally, one loss of DAA well clear occurred when the pilot had the TSD and DAA displays in different orientations, an issue only possible in the standalone display condition. While the nature of a standalone display certainly may have contributed to both of these losses of DAA well clear, the fact that there was only one occurrence in each of these LoDWC categories suggests that the overwhelming number of pilots were capable of avoiding these problems despite the fact that the DAA information was separate from the TSD.

VI. Conclusion

The present study was the conclusion of a series of experiments designed to identify the minimum information requirements for DAA displays and alerting. While previous studies have varied the alerting structure and conflict detection and resolution tools presented to the pilots, the current study was an attempt to validate the existing Phase 1 DAA MOPS in order to determine whether pilots can successfully carry out the DAA task when provided only with the minimum amount of information. This minimum information included standard traffic information (e.g., position, directionality, relative altitude, alert status) as well as suggestive maneuver guidance in the form of 'banding', which displayed to the pilot the threat level associated with nearby headings and altitudes. The pilots saw this DAA information in two different configurations: a standalone configuration and an integrated configuration, both of which are considered acceptable in the current draft of the DAA MOPS. Pilots were responsible for avoiding scripted conflicts while flying a mission route in hour-long experimental scenarios. Their response times and ability to remain DAA well clear of threats were recorded and reported here.

Pilots were found to respond proficiently to DAA alerting to threats to DAA well clear, maneuvering quickly and effectively regardless of display configuration. Pilots' initial response times and initial edit times were quick in both display configurations, although they were quickest in the integrated display condition. These response times dropped the most when pilots were responding to warning alerts rather than corrective alerts, indicating that they understood

the expectation that they should not wait to coordinate with ATC before maneuvering. Total edit times were seen to inflate when pilots were responding to warning alerts, an artifact of guidance to regain DAA well clear being available from JADEM for the first time in this series of studies. The aircraft response time and total response time metrics did show a moderate trend of the integrated display condition eliciting greater benefits compared to the standalone display condition as pilots responded to warning alerts, rather than corrective alerts. This suggests that an integrated display may disproportionately aid pilots as the urgency of their response to a threat increases. Nonetheless, both display conditions tested in the current study typically resulted in response times that were as quick, or quicker, than seen in Rorie, Fern and Shively⁶. Similarly, pilots were found to overwhelmingly avoid losses of well clear in both display conditions when provided with ample time. While the proportion of losses of well clear and severity of losses of well clear were both lower in the case of the integrated display, both display conditions were associated with high levels of safety.

Taken together, the results of the current study strongly support the currently-defined Phase 1 DAA MOPS as an appropriate set of minimum information requirements for UAS pilots. The results also support the allowance in the DAA MOPS for the DAA information to be provided in either an integrated or standalone display configuration. The presence of a DAA alerting structure that includes both a corrective and warning-level alert, as well as the constant availability of suggestive maneuver guidance in the form of heading and altitude bands, enabled pilots to consistently perform the DAA traffic avoidance function at a high level.

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