

Utility of Visual and Auditory Warning Alerting for Traffic Avoidance during UAS Operations

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Minimum Operational Performance Standards (MOPS) are being developed to support the integration of Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS). Input from subject matter experts and multiple research studies have informed display requirements for Detect-and-Avoid (DAA) systems aimed at supporting timely and appropriate pilot responses to collision hazards. DAA alerting is designed to inform pilots of potential threats to “DAA well clear”; the two highest alert levels – caution and warning – indicate how soon pilot action is required and whether there is adequate time to coordinate with the air traffic controller (ATC). Additional empirical support is needed to clarify the extent to which warning-level alerting impacts DAA task performance. The present study explores the differential effects of the auditory and visual cues provided by the DAA Warning alert, and performance implications compared to caution-only alerting are discussed.

INTRODUCTION

The projected expansion of Unmanned Aircraft Systems (UAS) for widespread civil and commercial use will soon extend routine operations across civilian airspace classes typically occupied by manned aircraft (FAA, 2013). Collaborative efforts between NASA and multidisciplinary partners in RTCA Special Committee 228 have guided the ongoing development of minimum operational performance standards (MOPS) that facilitate safe integration of UAS into the National Airspace System (UAS-NAS; RTCA, 2013). One key focus area in Phase 1 of the UAS MOPS (RTCA, 2017) was the development of a detect-and-avoid (DAA) system architecture that enables UAS compliance with existing federal aviation regulations, such as remaining ‘well clear’ with other aircraft (14CFR, 2004). Since unmanned pilots navigate UAS remotely without eyes onboard to make real-time visual assessments, it is critical that the information elements on their ground control station (GCS) interface support timely responses and advise appropriate actions against potential collision hazards. Performance data collected from a series of experiments by NASA’s UAS-NAS project have helped inform minimum DAA display alerting and maneuver guidance requirements necessary to remain and regain DAA Well Clear (DWC) during en route UAS operations (Bell et. al, 2012; Friedman-Berg et al., 2014; Santiago & Mueller, 2015; Fern et al., 2015; Rorie et al., 2016; Monk & Roberts, 2017; Rorie et al., 2017).

The Phase 1 DAA MOPS alerting logic was designed to inform pilots of whether an avoidance maneuver was needed to remain DWC. The threat levels within the alerting structure provide temporal information that indicate if a maneuver is necessary, and whether it is appropriate to contact ATC before doing so. The two highest alert levels that predict a loss of well clear are the Corrective DAA and DAA Warning alerts (see Table 1). The caution-level Corrective DAA alert applies to threats that require immediate attention, with the expected

action being to coordinate the resolution with the air traffic controller (ATC) before executing the maneuver. The warning-level DAA Warning alert is intended to indicate a higher sense of urgency. This is conveyed by a change in symbology and corresponding aural verbiage informing the pilot there is no longer time to coordinate with ATC and that an avoidance maneuver is immediately required to remain DWC.

Numerous performance benefits have been observed since the inclusion of the DAA Warning alert into the alerting structure, including faster response times, fewer DWC violations, and fewer ATC coordination attempts near the DWC threshold where immediate maneuvers were more appropriate (Fern & Rorie, 2015; Fern, 2016). These improvements may also be attributed to the other numerous refinements that made the DAA display more intuitive over time, however. Previous studies placed more focus on other aspects such as guidance presentation and interoperability with existing collision avoidance systems and did not directly observe the utility of the DAA Warning alert with a dedicated test manipulation. There is still debate as to whether it is necessary to include a warning-level alert in addition to the caution-level alerts in the DAA alerting logic for remaining DWC, as opposed to reserving warning-level alerts for collision avoidance events where a near midair collision is imminent. The present study seeks to provide clarity and empirical support on the issue by further exploring the differential effects of the warning-level symbology and aural alert on pilots’ DAA task performance.

METHOD

Participants

Fifteen pilots were recruited to participate in this study. They averaged 9,500 hours of manned flight experience in civil airspace and 7,600 hours in military operations.

Simulation Environment

Ground Control Station. The Vigilant Spirit Control Station (VSCS; Feitshans et al., 2008), developed by the Air Force Research Laboratory (AFRL), served as the GCS for the present study. The VSCS consisted of three components: the command-and-control interface, Tactical Situation Display (TSD) for traffic detection, and a status panel primarily used for secondary tasks.

Experimental Design

The present study utilized a one-way between-subjects design to examine the effects of DAA alerting level on pilots' DAA task performance.

Alerting Condition. The primary independent variable was the amount of warning-level information pilots received. Participants were split into 3 groups corresponding to the given alerting condition for that day. Pilots completed all scenarios with either Display 1 (D1 – Caution-only), Display 2 (D2 – Warning Aural), or Display 3 (D3 – Warning Aural and Symbol per Phase 1 DAA MOPS). The D3 condition contained the full alerting structure with the warning-level symbology and aural alerting as recommended in the Phase 1 DAA MOPS (see Table 1). Pilots in D1 were only presented with the Corrective DAA alert with no visual or auditory warning alerting, while D2 pilots received the auditory warning alert ('Maneuver Now') without any changes in symbology.

Phase 1 DAA MOPS Alerting Logic (D3)				
Symbol	Name	Aural Alert Verbiage	Time to LoDWC	Expected Action
	DAA Warning Alert	"Traffic, Maneuver Now" x2	25s	Maneuver prior to ATC contact
	Corrective DAA Caution Alert	"Traffic, Avoid"	55s	Contact ATC prior to maneuver
	Preventive DAA Alert	"Traffic, Monitor"	N/A	Monitor closely
	Guidance Traffic	N/A	N/A	
	None (Target)	N/A	N/A	

Table 1. Conflict alerting logic.

Procedure

Training. Once demographics and informed consent forms were completed, pilots received training on VSCS functionality and vehicle control inputs via slide presentation and hands-on demonstration. The basic training continued until pilots showed proficiency in maneuvering the aircraft and performing secondary tasks. Pilots were then trained on the assigned DAA alerting structure and given test encounters

with traffic displayed on the TSD. A 20-minute practice session was completed before beginning experimental trials.

DAA Pilot Task. Pilots completed four 45-minute scenarios with their assigned alerting configuration. The primary task was to navigate a simulated MQ-9 Reaper along a pre-filed flight path while maintaining DWC (0.66nmi horizontal separation, 450 ft. vertical separation, 35s modTau) from nearby traffic. Each scenario consisted of 15 encounters scripted to lose DWC without pilot action. As shown in Table 2, the encounters were split equally into five Use Cases which varied based on time-to-LoDWC in seconds(s) at first alert. The encounters in Use Cases A and B started as a DAA Warning alert, and thus were considered to be threats of higher severity. The encounters in the remaining Use Cases C-E registered first as a Corrective DAA alert and were considered to be threats of lower severity. All maneuver guidance available on the TSD was independent of the GCS command-and-control interface, so pilots were required to manually input all maneuvers when resolving conflicts. Pilots were trained to coordinate their maneuvers with a confederate air traffic controller, time permitting. D1 pilots without any warning alerting were trained to use their discretion on whether they had adequate time to coordinate with ATC prior to maneuvering. Pilots in D2 and D3 had either auditory or visual warning-level information to indicate an encounter warranted immediate action. Secondary tasks (e.g. responding to mission-related chat messages and changing backup radio frequencies) were also included as part of the experiment.

Use Cases	Warning Range		Corrective Range		
	A	B	C	D	E
Time-to-LoDWC	15s	25s	35s	45s	55s

Table 2. Time to LoDWC at first alert by Use Case.

MEASURES

Measured Response Time (MRT)

Initial Response Time (Initial RT). Initial RT is the amount of time elapsed between the onset of a Corrective DAA or DAA Warning alert and the pilot's initiation of a navigational edit to the vehicle control interface.

Initial Edit Time. Initial Edit Time refers to the amount of time elapsed between the start of the navigational edit and completion of the *first* upload to the vehicle control interface.

Aircraft Response Time (Aircraft RT). Aircraft RT refers to the time elapsed between the onset of a Corrective DAA or DAA Warning alert and the *first* navigational upload to the control interface.

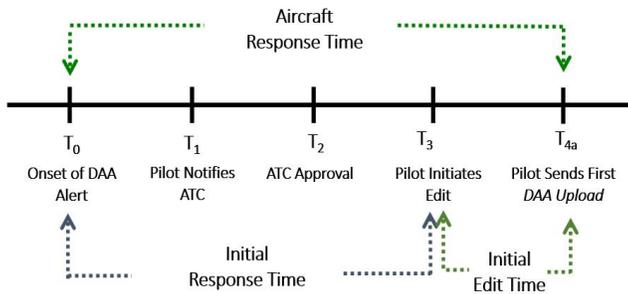


Figure 1. Pilot Interaction Timeline.

ATC Coordination

In the context of the alerting logic, ATC coordination is considered appropriate prior to maneuvering for less severe threats outside of 25s-to-LoDWC. The rate at which pilots prioritized coordination above maneuvering for caution-level and warning-level threats was compared across alerting conditions.

Losses of DAA Well Clear (LoDWC)

LoDWC Proportion. The proportion of LoDWC out of all intruders predicted to lose DWC was collected across alerting conditions.

LoDWC Type. The reasons for DWC violations in which the pilot was found responsible were classified into the following categories:

- Inappropriate Coordination – coordinating with ATC prior to maneuvering within the warning threshold;
- Ineffective Maneuver – inaccurate heading or altitude resolution with sufficient time to remain DWC;
- Slow Response – prioritized maneuver appropriately with no late intruder acceleration (Use Case A), but resolution not uploaded in time to avoid DWC.

RESULTS

The measured response, coordination, and separation metrics were compared across the three alerting conditions. Response time metrics were analyzed using a one-way Analysis of Variance (ANOVA) with an alpha level of .05. Tukey HSD post hoc comparisons are reported where significant main effects are found. No significant differences were found between the D2 and D3 alerting conditions for any of the measured response metrics. Descriptive statistics are reported for the coordination and separation performance metrics. It should be noted that the alerting conditions yielded minimal performance differences for avoidance of the less severe encounters that first registered as caution-level threats (Use Cases C-E). This finding was expected, as the primary variable under manipulation (i.e. warning-level perceptual signals) was not apparent on the DAA display until time-to-LoDWC was within the DAA Warning threshold of 25 seconds. Therefore, the current section shall focus heavily on pilot performance with the more severe encounters in Use Cases A & B - where the impact and utility of the DAA Warning alert was most pronounced.

Measured Response Time (MRT)

Initial RT. There was a significant main effect of alerting condition on Initial RT when avoiding severe conflicts, $F(2, 299) = 29.40, p < .001$. Specifically, pilots initiated edits against severe threats faster with the D3 ($M = 3.05s, SE = 0.17s$) and D2 displays ($M = 3.75s, SE = 0.22s$) compared to D1 ($M = 5.95s, SE = 0.39s$).

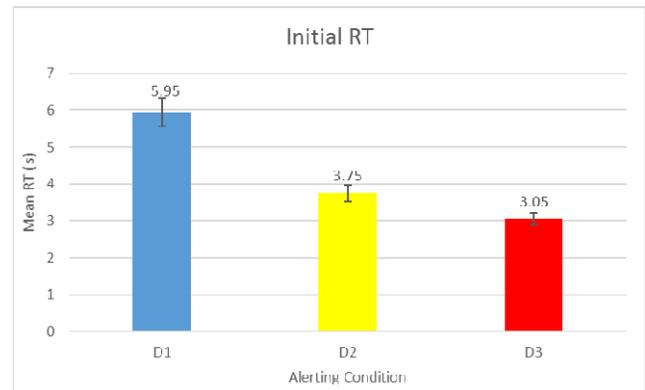


Figure 2. Initial RT by Condition (Use Cases A/B).

Initial Edit Time. There was also a significant main effect of alerting condition found on Initial Edit Time, $F(2,299) = 16.71, p < .001$. Pilots completed their first edits against severe threats significantly quicker with the D3 ($M = 5.01s, SE = 0.20s$) and D2 displays ($M = 5.15s, SE = 0.19s$) compared to D1 ($M = 6.69s, SE = 0.28s$).

Aircraft RT. Alerting condition did have a significant main effect on Aircraft RT, $F(2, 299) = 51.74, p < .001$. Pilots were quicker to upload their initial navigation command to the aircraft in response to severe threats with the D3 ($M = 8.06s, SE = 0.29s$) and D2 displays ($M = 8.90s, SE = 0.24s$) compared to D1 ($M = 12.64, SE = 0.44s$).

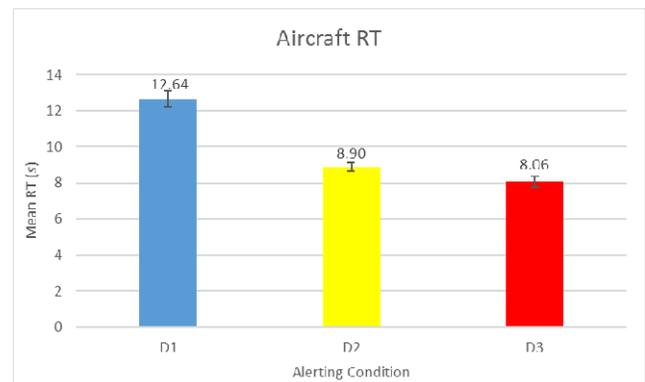


Figure 3. Aircraft RT by Condition (Use Cases A/B).

ATC Coordination

Pilots presented with visual and auditory warning-level alerting in the D3 conditions was much more likely to respond appropriately to severe threats within 25s-to-LoDWC (i.e., maneuver before coordinating with ATC) compared to the D2 group with auditory warning-level alerting and D1 group with

Caution-only alerting (Figure 4). Pilots with D3 alerting attempted ATC coordination before avoiding a severe threat only 12% of the time, while ATC coordination was attempted for 76% and 42% of severe encounters in D1 and D2, respectively. Furthermore, pilots with D3 alerting were also most consistent with contacting ATC prior to avoidance maneuvers against caution-level threats (coordinated 94% of the time; Figure 4) compared to D1 and D2 (coordination rates of 87% and 84%, respectively).

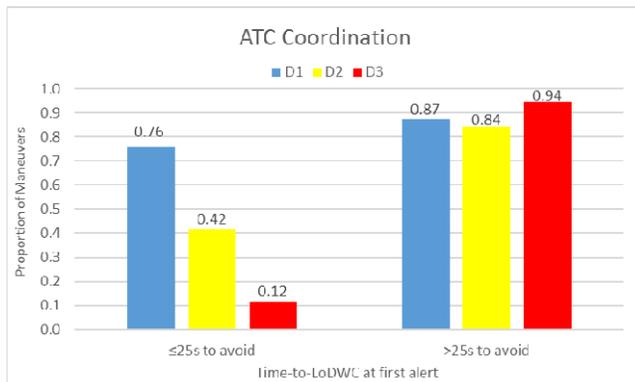


Figure 4. ATC Coordination Rate by Condition and Time-to-LoDWC.

Losses of DAA Well Clear

LoDWC Proportion. 96% of the total pilot-responsible LoDWC across all conditions occurred when threats alerted within the warning threshold in Use Cases A-B. Among these severe cases, D3 pilots had a much smaller LoDWC proportion (15.5%) compared to D1 (47.1%) and D2 (40.8%). There was only one LoDWC per alerting condition for less severe encounters outside of this range, all occurring in Use Case C.

LoDWC Type. Inappropriate coordination accounted for the majority of LoDWC occurrences, and occurred most in the D1 condition (Table 3). The D3 alerting greatly reduced the amount of LoDWC due to coordination attempts compared to D1 and D2. Variable performance with regard to ATC coordination and ineffective maneuvers accounted for the majority of DWC violations in the D2 condition. There were no LoDWCs due to slow response when pilots had either D2 or D3 alerting.

	Inappropriate Coordination	Ineffective Maneuver	Slow Response	TOTAL
D1	39	2	2	43
D2	17	15	0	30
D3	4	2	0	6
ALL	60	19	2	79

Table 3. Total LoDWC by Condition and LoDWC Type.

DISCUSSION

Overall, the findings reveal benefits associated with warning-level alerting when it is presented on the display. As noted, caution-level alerting was adequate in assisting pilots in

remaining DAA well clear against intruders outside of 25 seconds from the DWC boundary. The alerting conditions yielded minimal performance differences at these encounter ranges where the information being presented was identical. The high number of ineffective maneuvers in the D2 condition compared to D1 and D3 (Table 3) are attributed to individual differences, as the majority of these cases are isolated to one poor trial each from two participants. In these two particular data runs, they used their discretion to upload vertical resolutions as the initial avoidance maneuver, regardless of intruder range. This was not always a viable option to avoid a loss of DAA well clear against encounters of higher severity without a secondary heading change (as reflected in the conflict bands), given the aircraft's vertical speed performance of 1000 feet per minute (fpm). Performance in the subsequent trials stabilized once they realized the consistent negative outcome of this strategy and acted accordingly.

Nevertheless, it is the higher severity encounters where the impact of warning-level alerting and its timing threshold become more pronounced. For the high severity threats (i.e., first alerting less than 25s from the DWC boundary), faster (and less variable) Initial and Aircraft RTs were associated with an additional warning-level alert of either kind. The pilot interaction with the control interface and subsequent aircraft response was more immediate in the warning alerting conditions (D2 and D3). Similar to the trend seen in previous studies, pilots were far less likely to prioritize ATC coordination above maneuvering near the DWC boundary when the warning alerts were active, especially when it included the visual cue. Pilots were most likely to violate DWC due to inappropriate coordination attempts when presented with the Caution-only alerting in D1, as this condition left task prioritization solely to pilot discretion without the updated temporal information provided by the warning alert. The increased variability in response times to severe threats with the Caution-only alert further suggests that the warning information was a useful indicator of whether there was adequate time for ATC coordination prior to maneuvering. DAA task performance was directly impacted, as failure to prioritize these actions appropriately was the primary cause of DWC violations. Also, pilots with D3 alerting had the highest rate of ATC coordination for caution-level threat avoidance, which implies a clear understanding of the appropriate initial action to take for both the nominal and more severe conflicts.

While the auditory warning alert in D2 improved separation performance compared to D1, benefits were strongest in the D3 condition where the auditory cue was accompanied by a red DAA Warning symbol. Pilot feedback highlighted the potential for missing an auditory upgrade in threat severity (from caution to warning) while actively communicating with ATC or performing a secondary task. Pilots also noted that warning-level alerts with a change in symbology are more attention-grabbing because the three different DAA aural alerts within the structure all begin with the same verbiage ("Traffic, Monitor/Avoid/Maneuver Now"). The red symbol matched their mental model of what indicates increased severity in current operations, and it further distinguishes from the two yellow caution-level alerts that

precede it in this alerting structure. The unique visual and auditory alerts for these time-critical encounter states that require immediate awareness are also consistent with the existing design requirements for flight crew alerting functions (FAA, 2010). Performance implications in the present study promote the effectiveness of the DAA Warning's visual and aural alerting for Phase I DAA systems, and should be considered during future implementations of other system classes for UAS operations in the NAS.

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