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# UAS Pilot Traffic Avoidance Maneuver Preferences, Response Times, and ATC Interaction Decisions

Kevin W. Williams[1]
Eamon Caddigan[2]
Carolina Zingale[3]

[1]Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

[2]T.G. O'Brien & Associates, Inc.
Westcliffe, CO 81252

[3]Williams J. Hughes Technical Center
Federal Aviation Administration
Atlantic City, NJ 08234

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16. Abstract

This report is a follow-on analysis of maneuver data, pilot response time data, and air traffic control interaction data that was collected in a research study by Williams, Caddigan, and Zingale (2017). That study was conducted to assist the standards development group, RTCA Special Committee 228, in the establishment of minimum information requirements for Unmanned Aircraft System (UAS) Detect and Avoid (DAA) traffic displays. The research tested four different display configurations. These were a baseline display, and the baseline display with either a closest point of approach (CPA) indication, avoidance area information, or banding information that provided horizontal and vertical vectors to avoid to prevent a loss of well clear from an intruder aircraft. Details of that research are provided in Williams et al. (2017).

The follow-on analysis of maneuver data showed that pilots were influenced by the type of display they were using. Both the baseline and CPA displays biased pilots more toward vertical avoidance maneuvers while the avoidance area and banding displays biased pilots toward horizontal avoidance maneuvers. In addition to display type, avoidance maneuvers were influenced by encounter geometry. Pilots were biased toward vertical maneuvers if ownship was descending at the time of the encounter. They were biased toward horizontal maneuvers if the intruder was climbing or descending. Finally, there was some evidence to suggest that pilots were biased toward vertical maneuvers when time to closest point of approach to the intruder was less than 60 seconds.

The maneuver response time data lend additional support to the use of suggestive maneuver information as part of the minimum information requirements for DAA traffic displays. Again, as was the case with well clear violation data reported in Williams et al. (2017), support was found for both the banding and avoidance area displays when it was shown that pilot maneuver responses were significantly faster using those displays than when using the baseline display. Ramifications of these results for DAA display design are discussed.

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## TABLE OF CONTENTS

**LIST OF FIGURES**

## LIST OF TABLES

## LIST OF ACRONYMS

| | |
|---|---|
| ANOVA | Analysis of Variance |
| ATC | Air Traffic Control |
| CAT | Collision Avoidance Threshold |
| CDTI | Cockpit Display of Traffic Information |
| CFR | Code of Federal Regulations |
| CPA | Closest Point of Approach |
| DAA | Detect and Avoid |
| DAIDALUS | Detect and Avoid Alerting Logic for Unmanned Systems |
| FAA | Federal Aviation Administration |
| ICOMC2 | Insitu's Common Open Mission Management Command and Control |
| MOPS | Minimum Operational Performance Standards |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| NIEC | NextGen Integration and Evaluation Capability |
| NMAC | Near Mid-Air Collision |
| RTCA | RTCA, Inc. |
| RTTS | Real Time Tracking Surveillance |
| SAA | Sense and Avoid |
| SME | Subject Matter Expert |
| SST | Self-Separation Threshold |
| TCAS | Traffic Collision Avoidance System |
| TCPA | Time to Closest Point of Approach |
| TGF | Target Generation Facility |
| UA | Unmanned Aircraft |
| UAS | Unmanned Aircraft System |
| UATD | Unmanned Aircraft Traffic Display |
| WCV | Well Clear Violation |
| WJHTC | Williams J Hughes Technical Center |

## EXECUTIVE SUMMARY

A research study was conducted to assist the standards development group, RTCA Special Committee 228, in the establishment of minimum information requirements for Unmanned Aircraft System (UAS) Detect and Avoid (DAA) traffic displays (Williams, Caddigan, & Zingale, 2017). Such displays are necessary for complete access to the National Airspace System (NAS) and conformance to Title 14 Code of Federal Regulations (14CFR) Part 91.113, which requires pilots to "see and avoid" other aircraft.

The experiment tested four different display configurations. The baseline display contained the following pieces of information:

- Aircraft ID
- Position (range and bearing) indicator
- Relative altitude
- Heading indicator (e.g., chevron)
- Climb/descend indicator (e.g., up/down arrow)
- Collision threat status alert
- Visual projection of future position(s)

The other three displays contained everything available in the baseline display plus an additional type of information. This additional information was (1) an indication of the Closest Point of Approach (CPA) between ownship and an intruder aircraft, (2) avoidance area information indicating areas to avoid preventing a loss of well clear from another aircraft, or (3) banding information indicating horizontal and vertical vectors to avoid preventing a loss of well clear.

In addition to testing four display types, the experiment also included pilots either having large UAS (> 55lbs.) piloting experience or that were instrument-rated manned aircraft pilots with no large UAS experience. The experiment also manipulated the type of control station interface that was used, with half of the participants using a General Atomics, Predator control station and the other half using the Insitu company's ICOMC2 control station.

While the primary approach of the study was to establish minimum information requirements recommendations using data regarding traffic avoidance effectiveness, human-in-the-loop (HITL) studies like this provide a wealth of data in addition to that used to measure effectiveness. The Williams et al. (2017) report also included subjective data regarding pilot display preferences and usability, both subjective and objective data about the effectiveness, acceptability, and usability of the visual and auditory alerts used in the study, and subjective data about the maneuvers used for traffic avoidance.

The current report looks at several more types of information from the Williams et al. (2017) study that were not included in that technical report. In this report, we looked at an analysis of the avoidance maneuver data, pilot response time data, and air traffic control (ATC) interaction data.

Unfortunately, the ATC interaction data were missing a large number of observations which prevented a full analysis of the results. The avoidance maneuver data showed that pilots were influenced by the type of display they were using. Both the baseline and CPA displays biased pilots

more toward vertical avoidance maneuvers while the avoidance area and banding displays biased pilots toward horizontal avoidance maneuvers. In addition to display type, avoidance maneuvers were influenced by encounter geometry. Pilots were biased toward vertical maneuvers if ownship was descending at the time of the encounter. They were biased toward horizontal maneuvers if the intruder was climbing or descending. Finally, there was some evidence to suggest that pilots were biased toward vertical maneuvers when time to closest point of approach to the intruder was less than 60 seconds.

The maneuver response time data lend additional support to the use of suggestive maneuver information as part of the minimum information requirements for DAA traffic displays. Again, as was the case with well clear violation data reported in Williams et al. (2017), support was found for both the banding and avoidance area displays when it was shown that pilot maneuver responses were significantly faster using those displays than when using the baseline display. We believe that enough support has been found to consider inclusion of the avoidance area symbology as a substitute for the banding symbology for these displays and would like to see future versions of the RTCA SC-228 DAA MOPS include this display symbology as well.

# UAS Pilot Traffic Avoidance Maneuver Preferences, Response Times, and ATC Interaction Decisions

## INTRODUCTION

A research study was conducted to assist the standards development group, RTCA, Inc. Special Committee 228, in the establishment of minimum information requirements for Unmanned Aircraft System (UAS) Detect and Avoid (DAA) traffic displays (Williams, Caddigan, & Zingale, 2017). Such displays are necessary for complete access to the National Airspace System (NAS) and conformance to Title 14 Code of Federal Regulations (14 CFR) Part 91.113, which requires pilots to "see and avoid" other aircraft. Williams et al. (2017) looked at the effect of four traffic display configurations on the ability of pilots to remain well clear of other traffic. One of the display configurations was a baseline, information only, configuration while the other three configurations included some type of what was called "suggestive information" that provided the pilot with a range of maneuver choices for avoiding conflicting traffic. In addition to the four traffic display configurations, the researchers also manipulated pilot type (manned vs. unmanned) and control station interface design to determine how they affected traffic avoidance success.

While the primary approach of the study was to establish minimum information requirements recommendations using traffic avoidance effectiveness data, human-in-the-loop (HITL) studies like this provide a wealth of additional data. For example, the Williams, et al., (2017) report also included subjective data regarding pilot display preferences and usability, both subjective and objective data about the acceptability and usability of the visual and auditory alerts used in the study, and subjective data about the maneuvers used for traffic avoidance.

In this report, we will look at several additional types of information from the Williams, et al., (2017) study that were not included in the technical report. We will look at an analysis of the avoidance maneuver data, pilot response time data, and air traffic control (ATC) interaction data. The avoidance maneuver data will indicate whether the type of maneuver used (horizontal, vertical, or speed change) was influenced by any of several factors that have been identified in previous research. The pilot response time data should provide further evidence of the effectiveness of different display items for assisting the pilot in the selection of an avoidance maneuver. The ATC interaction data will indicate whether ATC was contacted before or after an avoidance maneuver was initiated (or not at all) and whether the interaction had any effect on maneuver response time.

### Maneuver Preferences

Researchers have identified a number of factors that can influence the selection of a traffic avoidance maneuver in manned aircraft (Rantanen, Wickens, Xu & Thomas, 2004; Thomas & Wickens, 2008). Thomas and Wickens (2008) separate these factors into two main categories, explicit and implicit influences. Explicit influences are those in which a specific maneuver is provided to the pilot either through regulation, authority, or algorithm. In these instances, the pilot does not engage in a decision-making process to select the maneuver. Thomas & Wickens list four explicit influences. These are 1) FAA regulations (specifically 14 CFR Part 91.113 regarding see and avoid which directs pilots to make a right turn to avoid traffic), 2) ATC directive, 3) a Traffic

Collision Avoidance System (TCAS) advisory, or 4) a maneuver provided by a Cockpit Display of Traffic Information (CDTI) system.

Implicit influences will bias the pilot toward a particular maneuver but the pilot still engages in a decision-making process to select which maneuver is implemented. Thomas and Wickens (2008) list five implicit influences in the selection of an avoidance maneuver. The first of these is *stereotype*, which is described as a general dominant tendency to maneuver in a particular way, perhaps as a result of some combination of other influences, but which tends to be repeated once established, even under different conditions. One example of stereotype from the literature is the finding that non-pilots prefer left turns to avoid head-on conflicts (Beringer, 1978).

The second implicit influence is *cognitive complexity* and refers to a general tendency to select actions where the results are easier to understand and anticipate. This could be manifested in several ways for the selection of avoidance maneuvers, but one example would be an increased likelihood of selecting a vertical avoidance maneuver under conditions where there were several proximate aircraft at co-altitude with ownship. A horizontal maneuver would be more complex given the presence of the other aircraft at the same altitude.

The third implicit influence is the *anticipated safety* of the maneuver choice. One example is the reported tendency of pilots to maneuver vertically under conditions where the time until conflict is shorter (Thomas & Wickens, 2008), because of the fact that vertical maneuvers (specifically descents) have a shorter time constant than speed or horizontal maneuvers (Krozel & Peters, 1997).

*Display format* is the fourth implicit influence. Early studies of maneuver choices demonstrated an overwhelming tendency for participants to choose a horizontal maneuver over a vertical maneuver (Palmer, 1983; Smith, Ellis, & Lee, 1984; Wing, Barmore, & Krishnamurthy, 2002). Much of this tendency was attributed to the use of a 2-D plan-view map that provided no information regarding vertical separation to the pilot. Support for this assertion was provided by studies of 3-D perspective displays showing vertical separation graphically (e.g., Ellis, McGreevy, & Hitchcock, 1987) or coplanar displays that provide a 2-D representation of vertical separation (Wickens et al., 2002). Use of such displays resulted in significant increases in vertical maneuvering relative to displays not containing a graphical representation of vertical separation.

The fifth implicit influence listed by Thomas and Wickens (2008) is *conflict geometry*. The relationship of other aircraft to ownship can obviously prevent the selection of a specific maneuver. However, it is not clear whether there is an effect on a maneuver category. For example, it is not clear whether the presence of traffic that prevents ownship from climbing makes descending more or less likely than a heading or speed change.

In addition to internal and external influences listed for manned aircraft traffic avoidance, unmanned aircraft operations have some other potential unique influences that could contribute to the selection of an avoidance maneuver. For example, the *pilot interface* for UAS control stations is not currently standardized. This has led to a variety of control and display designs that differ drastically in their complexity and consistency. Input procedures for providing maneuver commands to an unmanned aircraft (UA) differ from system to system and, for some systems, differ across maneuver axes. That is, for some systems, inputting a horizontal maneuver might be more complex and take longer than inputting a vertical or speed maneuver. These differences could influence maneuver selection for pilots flying these systems. Some evidence for this was found by Thomas and Wickens (2008), with their use of a waypoint manipulation user interface, as was noted by Kuffner, Guendel, and Darrah (2016).

A second factor potentially influencing UAS pilot maneuver selection that was suggested from NASA studies (Fern, Rorie, Pack, Shively, & Draper, 2015; Rorie & Fern, 2015; Rorie, Fern, & Shively, 2016; Santiago & Mueller, 2015) is *training* (Lisa Fern, personal communication). Pilot interviews of UAS pilots participating in the NASA studies revealed that, because of differences in flight performance characteristics of their aircraft, Predator pilots were trained to avoid traffic primarily by making heading changes while Global Hawk pilots were trained to change altitude. NASA personnel noted a strong bias in their studies for horizontal avoidance maneuvers and believed a primary reason was their use of mostly Predator pilots.

Another factor unique to UAS is *control link management*. The need to maintain or re-establish the control link can sometimes prevent the use of certain aircraft maneuvers. This is especially true for systems controlled by direct line of sight with an antenna transmission. Pilots of these systems have to be aware of terrain or human-made features that could block the signal. For example, maneuvering below a ridge line or behind a mountain could interrupt the control link and send the aircraft into a lost link procedure.

### Pilot Response Time to Perform Avoidance Maneuvers

Knowledge of the approximate amount of time that it takes for a pilot to decide on, and perform an avoidance maneuver is important. This response time factors into deciding when to trigger alerts and how much advance notice is required for the pilot to acknowledge the alert and adequately react to traffic conflicts. The amount of advance notice needed can determine the requirements for radar strength or other equipment used to detect the traffic.

### Interacting with Air Traffic Control

It is expected that air traffic controllers will constitute the first, and most important line of defense against the potential for aircraft to get too close to each other. For this reason, most large UAS operations in the NAS will be conducted under instrument flight rules (IFR) which requires the filing of a flight plan and regular contact with ATC during the flight. For this reason, participants in this study were told they were on an IFR flight plan and that, if they had enough time to do so, they should contact ATC before making an avoidance maneuver, which would require a deviation from the flight plan. However, because participants were aware that there would always be a traffic conflict, contact with ATC was irregular, especially regarding requests to deviate from the flight plan. Despite this, review of participant interaction with ATC is necessary to understand pilot response times and, potentially, maneuver decisions.

## Hypotheses

Because the primary purpose of the experiment was to test the effectiveness of particular traffic display configurations, there were no particular a priori expectations regarding both maneuver preferences or ATC interactions. However, a post hoc review of maneuver preference literature showed that certain maneuver preferences were to be expected. For example, Guendel, Kuffner, and Maki (2017), summarizing findings from several manned pilot traffic avoidance maneuver preference studies, list the following preferences:

- Single-axis vertical or horizontal maneuvers (e.g., climb) were preferred over multi-axis maneuvers (e.g., climb and turn together),
- Vertical maneuvers were preferred over horizontal maneuvers,
- No preference between right and left turns regardless of right-of-way rules, and
- Little preference for airspeed maneuvers.

These preferences are also listed in Thomas and Wickens (2008), with the exception that a preference of vertical over horizontal maneuvers is influenced by the amount of time available to maneuver (Krozel and Peters, 1997), with less time leading to a higher likelihood for a vertical maneuver. In addition to these preferences, Thomas and Wickens (2008), as mentioned earlier, also suggest that display format might influence maneuver preference. In the current study, there is no vertical situation display available to the pilot. The only way that vertical separation is apparent to the pilot is from relative altitude information available next to each target (see Figure 1 in Methods section). According to Thomas and Wickens (2008), this type of display might bias pilots into making horizontal maneuvers over vertical maneuvers.

Because the suggestive flight display information was expected to produce more effective avoidance responses than the baseline display, it was expected that these displays would also allow faster responses by the pilot to select an avoidance maneuver. Faster response times for suggestive information displays have been found previously by NASA researchers as well (Rorie, Fern, & Shively, 2016; Rorie, Fern, Shively, & Santiago, 2016).

# METHOD

## Participants

Thirty-two pilots were recruited for the study. Sixteen of the pilots had UAS experience and the other 16 were instrument-rated manned aircraft pilots with no UAS experience. The sample size was based on the need to have enough participants sufficient to yield robust data while meeting cost, personnel, and time constraints. We recruited manned pilots based only on having a current instrument rating, while UAS pilots were required to have mission experience, 200 hours flight experience, and have a current manned flight certification within the last 3 years. Unmanned pilots recruited for the Predator simulator were experienced Predator pilots. Of these, five flew the MQ-9, one flew the MQ-1B, and two had both MQ-9 and MQ-1 experience. However, because of the relative newness of the ICOMC2 simulation, no pilots could be found with operational experience with the ICOMC2. For this reason, the unmanned pilots recruited for the ICOMC2 had a mix of operational experience. Five of these pilots were Global Hawk pilots. One pilot flew the RQ-7B

Shadow UAS. One pilot flew the Scan Eagle, and one pilot flew both the Shadow and Scan Eagle UAS. Pilots were recruited from available sources including contract companies who have qualified participants on staff and the Department of Defense.

**Display Configurations**

The experiment tested four different display configurations (see Figure 1). The baseline display, Closest Point of Approach (CPA), Avoidance Area (Blob), and the Banding Display. The baseline display contained the following information regarding other traffic:

- Aircraft ID
- Position (range and bearing) indicator
- Relative altitude
- Heading indicator (i.e., chevron)
- Climb/descend indicator (e.g., up/down arrow)
- Collision threat status alert
- Visual projection of future position(s)

The other three display configurations contained all of the same information as the baseline display but with additional symbology. The Closest Point of Approach (CPA) display added an indication of where the closest point of approach would be for an intruding aircraft that is expected to violate the well clear boundary of ownship. This indication was given by the position of two dots on the traffic display. A cyan dot represented the future position of ownship at the time of CPA, while a yellow or red dot represented the intruder position at that time. A dotted cyan circle surrounding the ownship dot showed the approximate well clear boundary around ownship at time of CPA. Trajectory changes by either ownship or the intruder would cause the two points to either converge or diverge relative to each other. This convergence or divergence confirmed whether the maneuver would lead to an avoidance of a well clear violation.

It should be noted that, even though the traffic display could be oriented in either a north-up or track-up position, participants were instructed to leave the display in the north-up orientation. The primary reason for this was that the primary moving-map display in both control station simulations was oriented as north-up and thus could introduce confusion for the pilot if the orientation of the moving-map and traffic displays did not match.

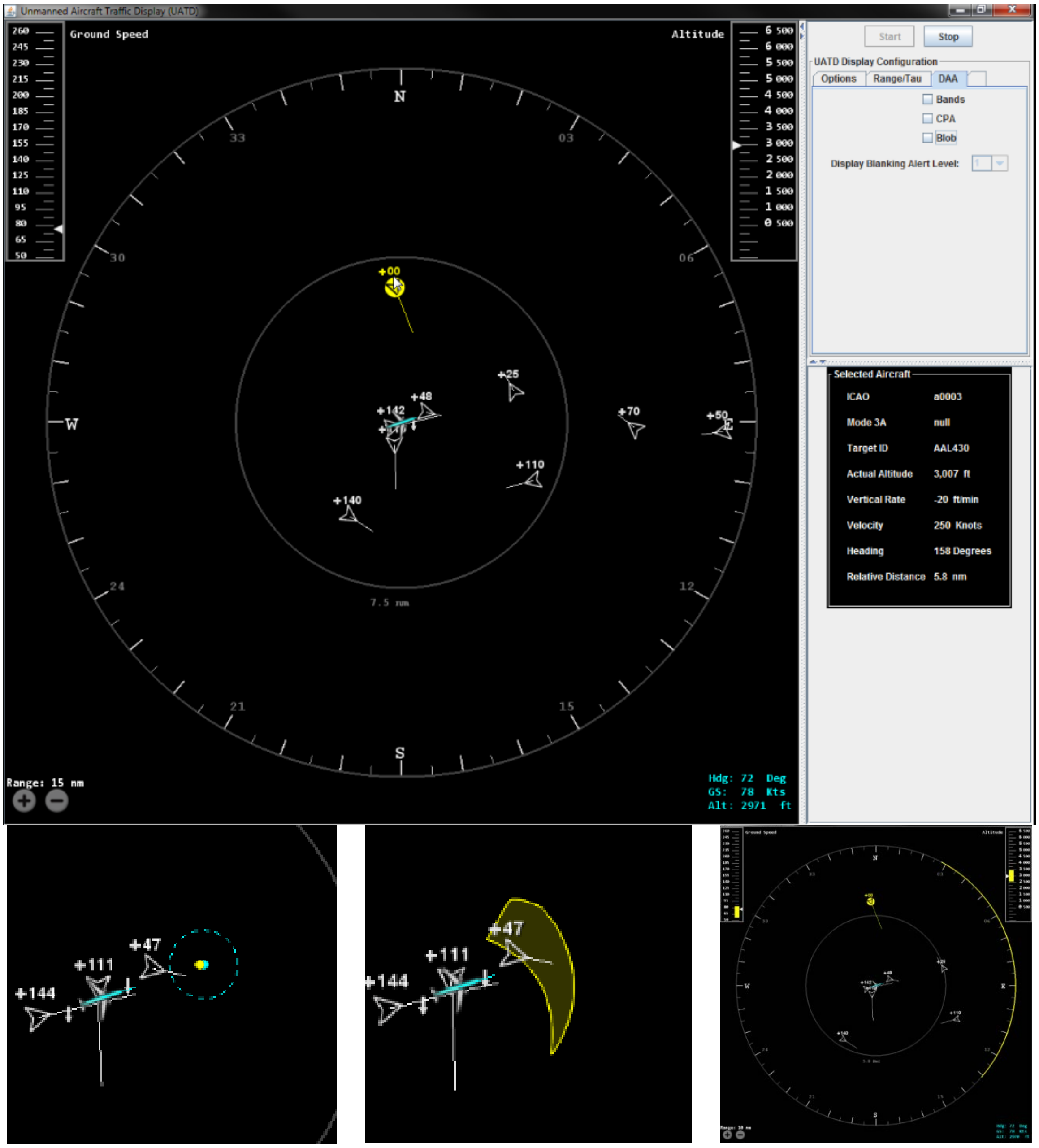


**Figure 1**. Display configurations used in the study. Shown counterclockwise from the top are: 1) Baseline display; 2) Closest Point of Approach configuration; 3) Avoidance Area (blob) configuration; and 4) Banding configuration. Note that the ownship symbol is underneath the cyan vector in the center of the display.

The Avoidance Area (Blob) display added a polygonal area showing where a loss of well clear would occur if neither ownship nor the intruder changed trajectories. The basic task of the pilot using this symbology was to maneuver ownship in such a way as to avoid entering the polygon.

The final display configuration, the Banding display, added three separate bands to the display. A heading band, shown on the right side of the display, was added to the edge of the range circle to provide an indication of which headings would lead to a well clear violation. An altitude band was added to the altitude tape in the upper right corner of the display to show which altitudes would lead to a well clear violation, and a speed band was added to the speed tape in the upper left corner of the display to indicate which speeds would lead to a well clear violation. The task of the pilot was to select a heading, altitude, or airspeed value that was not covered with a yellow band to avoid violating well clear. Note that the Banding display was the only one that provided suggested vertical maneuvers. The other two enhanced displays only provided suggestions regarding a horizontal maneuver, although for all the displays there was information available to the pilot regarding relative altitude and whether traffic was climbing or descending.

### Visual and Auditory Alerts

The alerting algorithms used for this study are collectively called DAIDALUS (Detect and Avoid Alerting Logic for Unmanned Systems) and were developed by NASA Langley Research Center personnel (Muñoz et al., 2015). DAIDALUS also provided the suggestive maneuver information used in the different display configurations. The DAA system used three levels of alerting for the presence of traffic. When an alert was triggered by the DAIDALUS algorithms, the traffic symbol corresponding to the intruder aircraft would change to one of the three shown in Figure 4, depending on the level of alert that was triggered, and an auditory alert would sound as well using the language in quotation marks under the symbol shown in Figure 2.

| | | |
|---|---|---|
|  |  |  |
| **Preventive DAA Alert***"Traffic, Monitor"* | **Corrective DAA Alert** *"Traffic, Avoid"* | **DAA Warning Alert** *"Traffic, Manveuver Now. Traffic, Maneuver Now."* |

**Figure 2**. Visual and auditory alerts used in the study.

The lowest priority alert, the Preventive DAA Alert, did not require an action on the part of the pilot but was intended to draw attention to an aircraft that needed to be monitored. The explanation of this alert that was provided in the Participant Instructions was as follows:

> "The lowest priority alert is the Preventive DAA Alert, which is accompanied by the aural alert, 'Traffic, Monitor'. This alert indicates that there is traffic on a course that will take it close to ownship but not close enough to violate the well-clear area of ownship. The pilot should monitor the movement of the traffic but does not need to perform any maneuvers to remain well clear."

The other two alerts, the Corrective DAA Alert and the DAA Warning Alert both indicated that a loss of well clear would occur if both aircraft remained on their current courses. The main difference between the two was that the Corrective DAA Alert was intended to provide more time for the pilot to make a maneuver than the highest priority DAA Warning Alert. In general, cockpit warning alerts require immediate action by the pilot. Participants were given instructions that, if they felt they had enough time to do so, they should contact air traffic control and request permission to deviate from their flight plan before performing the maneuver.

## Equipment

### Predator Station

The Predator Station pilot interface includes controls on the joystick but also accepts keyboard commands. For most flight commands, both the joystick and keyboard must be used. Figure 3 shows a picture of the Predator Control Station as it was configured for the study.

**Figure 3**. Predator control station with the traffic display on the right.

The moving map display at the top contained a depiction of the flight plan as well as a display used for changing aircraft heading. The center screen below the map display provided airspeed, altitude, heading, and vertical speed indications to the pilot. The bottom two screens provided information regarding the current control mode as well as other diagnostic information. The DAA traffic display can be seen on the right behind the joystick.

### ICOMC2 Station

Unlike the Predator control station, the ICOMC2 Station consists of a single screen. Figure 4 shows a picture of the ICOMC2 Station as it was configured for this study. Interaction with the system is accomplished using the mouse and keyboard. Inputting flight commands can be accomplished either by typing values in certain locations on the screen or by clicking and dragging with the mouse. The DAA traffic display is shown on the right.

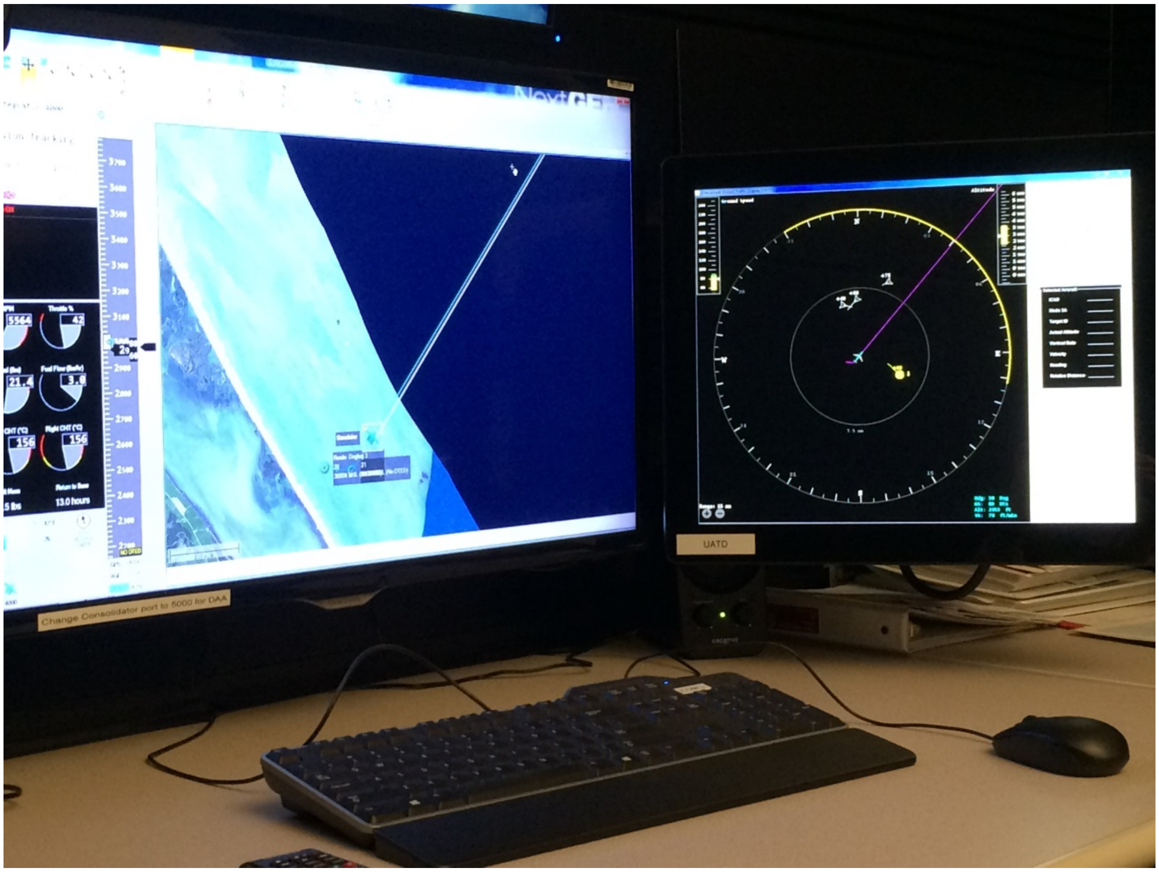


**Figure 4**. ICOMC2 control station with the traffic display on the right.

## Aircraft Models

In addition to differences in control station interface design influencing traffic avoidance effectiveness and procedures, differences in aircraft performance could also have an influence on pilot performance. The two control station simulators selected for the study use aircraft models that differ from each other to a great extent. The aircraft model used in the Predator control station was the General Atomics Predator B UA (Predator B) while the model used in the ICOMC2 control station was the Insitu Integrator UA (Integrator). Of particular relevance to this study, the turn and climb rates and cruise speeds of the two aircraft were markedly different. Table 1 provides the values of the aircraft models as they were established for the study.

**Table 1**. Configurable parameters used in the study, including the default values for the DAIDALUS algorithms.

| Configurable Parameters | Default Value set -DAIDALUS | Predator B | Integrator |
|---|---|---|---|
| Turn Rate | 3 deg/s | 2.5 deg/sec | 8.5 deg/sec |
| Bank angle | 30 deg | 30 deg | 30 deg |
| Horizontal acceleration | 2 $m/s^2$ | 2 $m/s^2$ | 2 $m/s^2$ |
| Vertical acceleration | 2 $m/s^2$ | 2 $m/s^2$ | 2 $m/s^2$ |
| Minimum ground speed | 50 kts | 75 kts | 58 kts |
| Maximum ground speed | 250 kts | 160 kts | 90 kts |
| Minimum vertical speed | -5000 fpm | -1500 fpm | -750 fpm |
| Maximum vertical speed | 5000 fpm | 1500 fpm | 450 fpm |
| Track step | 1 deg | 1 deg | 1 deg |
| Ground speed step | 1 kt | 1 kt | 1 kt |
| Vertical speed step | 10 fpm | used default | used default |
| Minimum Altitude | 500 ft | 500 ft | 1,000 ft |
| Maximum Altitude | 50,000 ft | 50,000 ft | 19,000 ft |

Note that even though the performance parameters of both aircraft models differed, both of the sets of aircraft performance specifications met the requirements for aircraft using a DAA system that have been established in Appendix D of the RTCA SC-228 DAA Minimum Operational Performance Standards (RTCA, 2016). While participants were not provided this table during the study, they did become familiar with the performance characteristics of their aircraft during training.

### Encounter Geometries

Each control station simulation (ICOMC2 and Predator) required 32 scenarios that were roughly matched in encounter geometry and the timing of the encounter. Pilots flew four distinct routes, all of which required a 49° turn at an initial waypoint followed by straight flight; two routes had a final bearing northwest and the other two had a final bearing northeast. The initial waypoint was reached approximately 40 s into the scenario after pilots had flown 2.0 nmi in the Predator or 0.8 nmi using the ICOMC2. One route included a descent of 2000 ft at the waypoint while the others were level flight. Participants flying the Predator flew at an altitude of 9000 ft on easterly routes (8000 ft on westerly routes), while participants flying the ICOMC2 system flew at 3000 ft on easterly routes (4000 ft on westerly routes).

**Table 2**. Encounter geometries used in the study.

| Encounter | Horizontal Geometry | Vertical Geometry Ownship | Vertical Geometry Intruder |
|---|---|---|---|
| 4HL | Head-on | Level | Level |
| 1HL | Head-on | Descending | Level |
| 3OL | Intruder Overtaking | Level | Level |
| 2OV | Intruder Overtaking | Level | Climbing |
| 2CL | Crossing | Level | Level |
| 4CL | Crossing | Level | Level |
| 1CL | Crossing | Descending | Level |
| 3CV | Crossing | Level | Descending |

There were a total of eight encounter geometries, two per route (see Table 2). Of the eight encounters, two involved a head-on intruder, one of which occurred while ownship was in level flight and the other occurred during ownship descent. The intruder overtook ownship in two encounters while ownship was in level flight; the intruder was also level in one encounter but was climbing in the second. The remaining four encounters featured a crossing intruder: one during ownship descent, one including a descending intruder; both ownship and intruder were in level flight otherwise.

Further variations in the scenarios were generated by altering the position of non-intruder "distractor" aircraft to create four versions of each encounter, thus resulting in 32 different scenarios. Each scenario contained 2-4 distractors, an intruder, and ownship. The mean number of aircraft across scenarios, including ownship, was 5.0.

### Procedure

After arriving at the facility, the participant viewed an introductory briefing. Participants then read and signed an Informed Consent Statement and completed a background questionnaire. Next, the participant was given familiarization training on the appropriate UAS simulator.

Participants completed eight encounter scenarios for each traffic display configuration. Order of the display configurations was counterbalanced across participants using a Latin Square design. Before flying the encounter scenarios for a particular display configuration, participants completed one or two practice scenarios to ensure complete understanding of the display configuration being flown.

All traffic scenarios began with the UA already in the air. Each scenario assumed that the aircraft was following an instrument flight plan. Each scenario contained one traffic encounter, maneuver/s to avoid the traffic, and command/s to return to course. To increase the difficulty of the encounter, the traffic display did not display any traffic other than ownship until the occurrence of a traffic alert. This prevented the pilot from anticipating a potential avoidance maneuver before the alert. The scenario ended once the aircraft had started its return to course. Depending on the encounter and pilot responses, each scenario lasted from three to six minutes.

After the last scenario in each display configuration, the participant completed the Post-Display Questionnaire. After completing all four of the display configurations, the participant was given a post-study questionnaire. More complete details of the procedure and questionnaires can be found in Williams et al. (2017).

## RESULTS

### Demographics

Recruiting of the participants was performed by an independent contractor based on requirements established by the researchers. When we began analyzing the demographic data from this study, one unexpected finding that became immediately clear was that our group of manned aircraft pilots was much older than the group of unmanned aircraft pilots. Table 3 presents the demographic summary statistics for the participants.

**Table 3**. Participant demographic summary statistics.

| Group | Mean Age (yrs.) (Median) | Age Ranges | Mean Total Flight Hours (Median) | Mean TCAS Experience (yrs) |
|---|---|---|---|---|
| Unmanned | 35 (35) | 29-46 | 2037.7 (1595) | 5.8 |
| Manned | 51.2 (55) | 34-77 | 12344.6 (9450) | 17.6 |

As can be seen in the table, the mean age for the manned pilots was approximately 16 years older than the unmanned pilots. In addition, and most likely because of this, the number of total flight hours for these groups was drastically different as well. All but two of the unmanned pilots had an IFR rating and all of them had training in manned aircraft. In regard to experience with TCAS, 13 of the 16 (81%) unmanned pilots reported they had experience with TCAS, while 14 of 16 (87.5%) manned pilots had TCAS experience. When asked about their level of familiarity with TCAS, 15 of the 16 (94%) manned pilots reported they were "very familiar" or "expert" with TCAS, but only 7 of 16 (44%) of the unmanned pilots reported the same. Seven of the manned pilots had experience with an ADS-B traffic display, but none of the unmanned pilots did. When asked if they had actually had to maneuver to avoid traffic (in real life), 12 of the 16 (75%) unmanned pilots responded "yes," and 15 of the 16 (94%) manned pilots responded "yes."

**Maneuver Preferences**

An analysis of maneuver preferences began by classifying the first maneuver performed by the pilot after a traffic alert occurred into one of three types. These types were a horizontal maneuver (bearing change), vertical maneuver (altitude change), or speed change maneuver. Out of the 1008 traffic trials performed, results showed that the most common maneuver was a horizontal maneuver (501 horizontal maneuvers, 49.7% of total), followed by a vertical maneuver (480, 47.6%), and then speed change maneuver (23, 2.3%). Four of the trials could not be classified due to problems with data integrity (0.4%).

To look at the effect of the dependent variables on maneuver preference, an analysis of variance (ANOVA) was performed on the percentage of horizontal maneuvers within each display type for each participant (i.e., each participant received 8 trials for each of the four display types, and the number of those trials in which a horizontal maneuver was performed was used to compute the percentage of horizontal maneuvers across the 8 trials). Results of the ANOVA showed a significant effect of display type on maneuver preference, $F(3,78) = 7.1$, $p < .001$. There were no other main effects or interactions.

Figure 5 shows the percentage of horizontal maneuvers by display type. Because approximately 97% of the maneuvers were either horizontal or vertical, subtracting the percentage of horizontal maneuvers from 100 provides a good indication of the percentage of vertical maneuvers used to avoid traffic. As can be seen from the figure, pilots using both the baseline and CPA displays were biased toward vertical avoidance maneuvers but when using the blob and banding displays were biased toward horizontal maneuvers. Pilots using the baseline and CPA display used a horizontal maneuver approximately 40% and 45% of the time respectively, but when using the blob and banding displays used a horizontal maneuver approximately 57% and

54% of the time respectively. Individual comparisons using a paired t-test showed that both the blob, $t(31) = 3.76$, $p < 0.001$, and banding, $t(31) = 3.46$, $p < 0.001$, displays were significantly more inclined toward horizontal maneuvers than the baseline display, while the CPA display was not, $t(29) = 0.42$, $p = 0.34$.

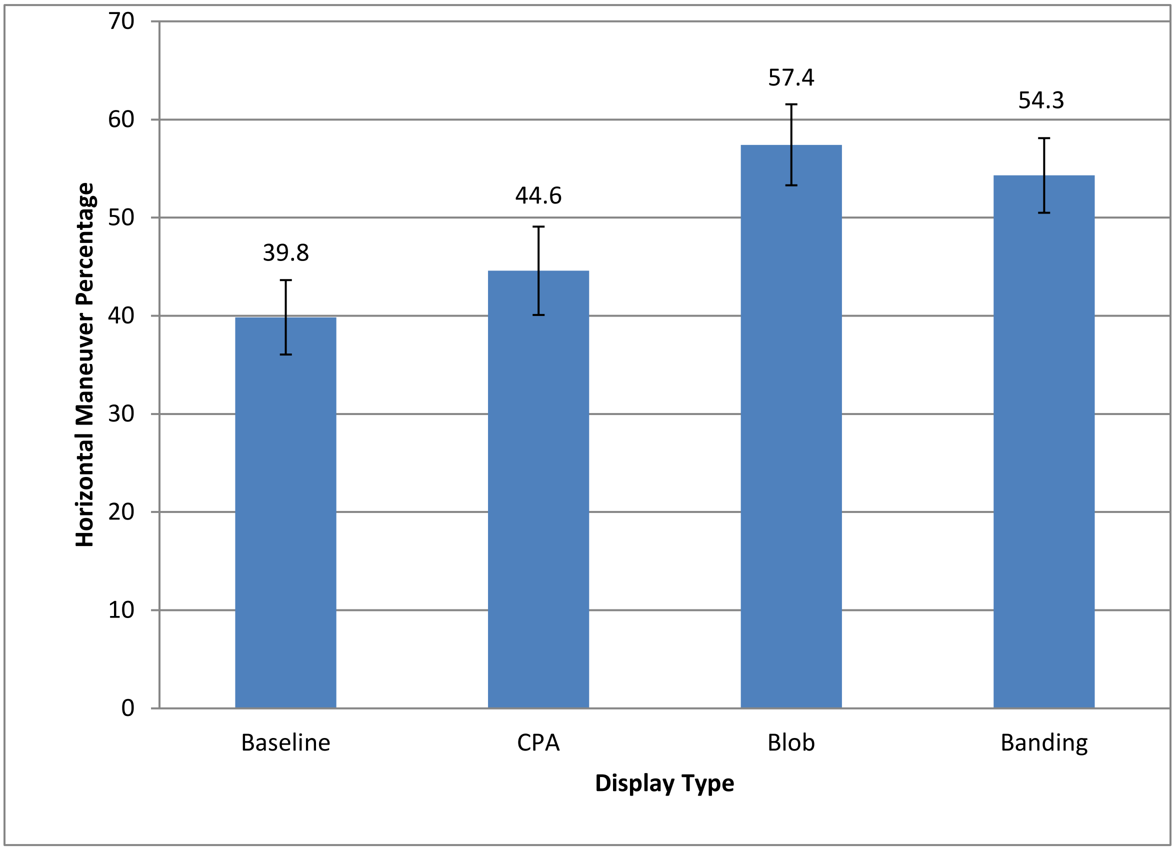


**Figure 5**. Horizontal maneuver preference as a function of display type.

### Influence of Conflict Geometry

To find out whether the conflict geometry had an effect on maneuver preference, we looked at each maneuver by the flight scenario that was used for that conflict. Table 3 shows the number of times a particular maneuver was selected for each scenario type. As can be seen in the table, some of the scenarios evoked a strong bias toward either a vertical (1HL) or horizontal (2OV) maneuver. In addition, the majority of speed maneuvers (14 of 23, 61%) occurred in scenario 1CL, in which ownship was descending and the intruder was crossing in front of ownship.

**Table 4**. Number of maneuver selections by flight scenario.

| Scenario<br>Maneuver | 1HL | 1CL | 2CL | 3OL | 4CL | 4HL | 2OV | 3CV |
|---|---|---|---|---|---|---|---|---|
| Horizontal | 6 | 46 | 63 | 74 | 51 | 74 | 106 | 81 |
| Vertical | 116 | 65 | 63 | 52 | 73 | 52 | 19 | 40 |
| Speed | 2 | 14 | 0 | 0 | 2 | 0 | 1 | 4 |

A chi-square analysis of these data was performed comparing the actual number of horizontal maneuvers to an expected number of horizontal maneuvers that was based on the overall percentage of horizontal maneuvers (49.7%, which yielded an expected number of horizontal maneuvers for each scenario of 62.625). The analysis computed a significant chi-square of 97.3, giving $p < 0.001$, thus supporting the hypothesis that maneuver selection was significantly influenced by conflict geometry.

Looking at which aspects of the conflict geometry had the largest effect on maneuver selection, we found that the two scenarios with the largest percentage of horizontal maneuvers (2OV and 3CV) had an intruder that was maneuvering vertically at the time of the encounter. In one of these scenarios (2OV), the intruder was overtaking ownship from directly behind and was climbing. In the other scenario (3CV), the intruder was crossing in front of ownship while descending. In both of these scenarios, ownship was flying straight and level at the time of the encounter. For the other two scenarios where the number of horizontal maneuvers was larger than the number of vertical maneuvers (3OL and 4HL), 3OL had the intruder overtaking ownship and 4HL had the intruder and ownship on a head-on collision course. In both scenarios, both ownship and intruder were flying straight and level.

For three of the scenarios (1HL, 1CL, and 4CL), the number of vertical avoidance maneuvers was more than the number of horizontal avoidance maneuvers. In two of those scenarios (1HL and 1CL) ownship was descending when the conflict occurred while the intruder was flying straight and level in either a head-on trajectory (1HL) or a crossing trajectory (1CL). As mentioned earlier, scenario 1CL also saw the most change of speed maneuvers by far. In scenario 4CL both ownship and the intruder were flying straight and level and the intruder was flying in a crossing trajectory relative to ownship. The final scenario (2CL) saw an equal number of horizontal and vertical avoidance maneuvers. Scenario 2CL was another scenario where both ownship and the intruder were flying straight and level and the intruder was in a crossing trajectory relative to ownship.

### Influence of Time Pressure

To estimate whether the amount of time available to maneuver had any effect on maneuver preference, we looked at the maneuver selections as a function of time to closest point of approach (TCPA). Figure 6 shows the percentage a maneuver axis (horizontal or vertical) was selected as a function of time to closest point of approach.

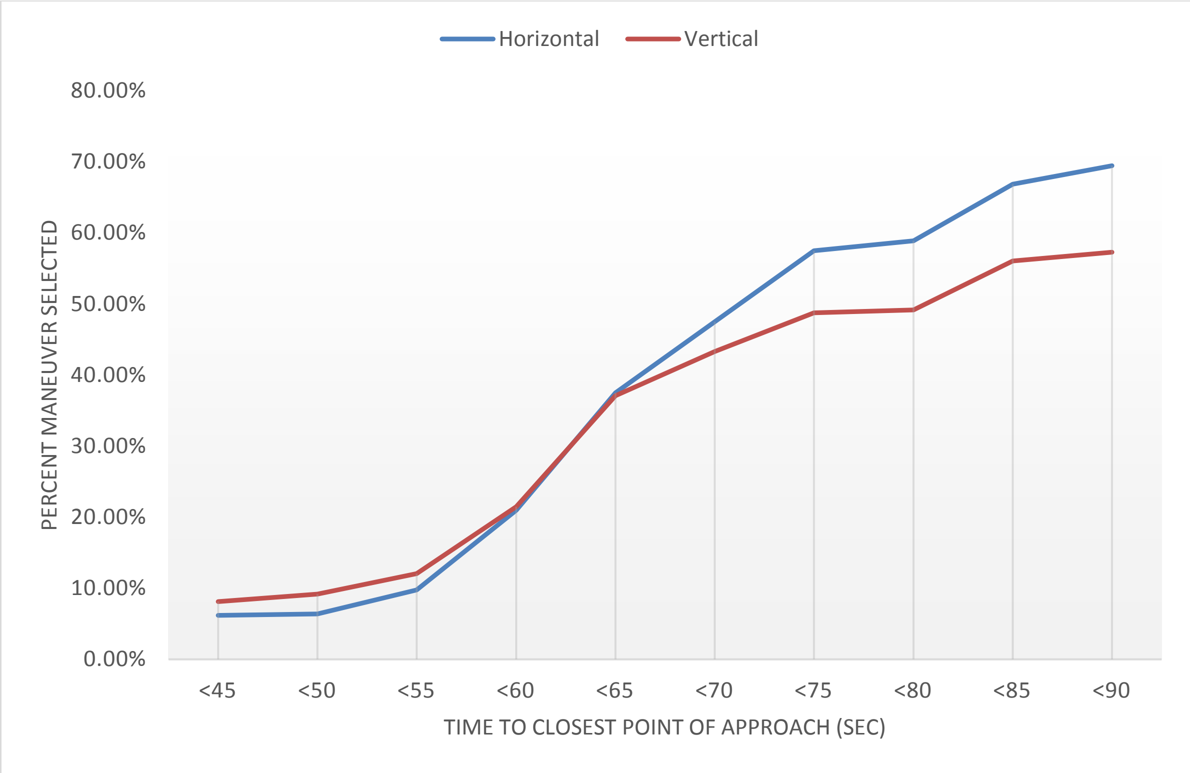


**Figure 6**. Percent maneuver selected as a function of time to closest point of approach.

As can be seen in Figure 6, when TCPA was less than 60 seconds, there was a tendency for pilots to select a vertical maneuver over a horizontal maneuver. Above a TCPA of 65 seconds, this tendency is reversed. A two-sample Kolmogorov-Smirnov test shows that the distribution of horizontal and vertical maneuvers differs as a function of TCPA ($D = 0.135$, $p < 0.001$).

## Response Time Data

Response time was measured from when the first traffic alert was activated until the aircraft began an avoidance maneuver. An ANOVA of the response time data found a significant difference in response time as a function of display type, $F(3, 78) = 6.058$, $p = 0.001$. In addition, the analysis revealed a significant interaction between display type and control station type, $F(3, 78) = 4.413$, $p = 0.006$, and a significant main effect of both control station type, $F(1, 26) = 14.742$, $p = 0.001$, and pilot type, $F(1, 26) = 6.75$, $p = 0.015$.

Figure 7 shows the mean response times for each of the four display types. While these response times are not assumed to be representative of actual flight conditions, the comparisons across display types are still considered relevant. As can be seen in the figure, pilots responded the slowest to the baseline and CPA displays (20.07 and 19.53 seconds respectively), and fastest with the blob and banding displays (16.61 and 17.61 seconds respectively). Individual comparisons using paired t-tests showed a significant difference in response time between the baseline and blob displays, $t(31) = 2.81$, $p = 0.004$, and between the baseline and banding displays, $t(31) = 1.79$, $p = 0.042$, but not between the baseline and CPA displays, $t(29) = 0.13$, $p = 0.55$.

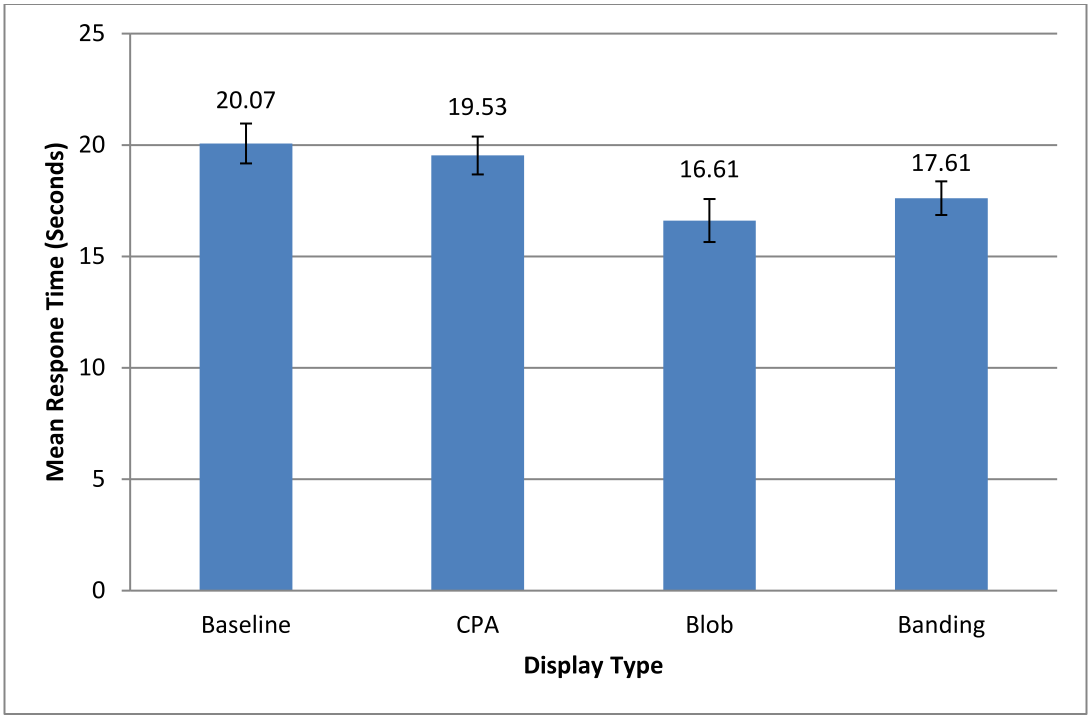


**Figure 7**. Mean response time for each display type.

Figure 8 shows the significant interaction between display type and control station type. Looking at the figure, we see that the interaction effect is due primarily to the response times for the CPA and banding displays while flying the Predator control station. Whereas most measures of performance show a clear advantage of the blob and banding displays over the baseline and CPA displays, the response time results with the Predator station show a slightly lower response time with the CPA display over the banding display.

In addition, to the interaction, Figure 8 clearly shows the significant advantage of the Predator station over the ICOMC2 station in response time. Averaging across all the display types, the mean response time for pilots using the ICOMC2 station was 20.88 seconds and for pilots using the Predator station was 16.05 seconds. Speculation regarding this effect will be presented in the discussion section.

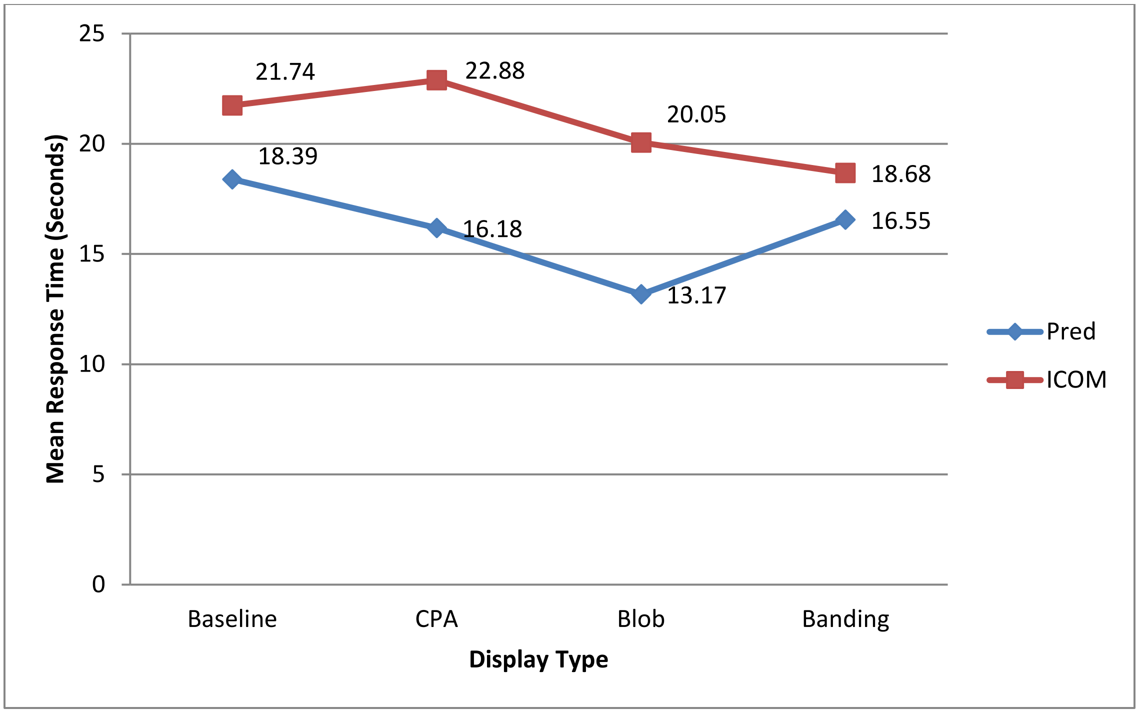


**Figure 8**. Display type by control station type response time interaction.

Figure 9 shows the main effect of pilot type on response time. As can be seen in the figure, the IFR-rated manned aircraft pilots responded approximately 3 seconds slower than the UAS-experienced pilots.

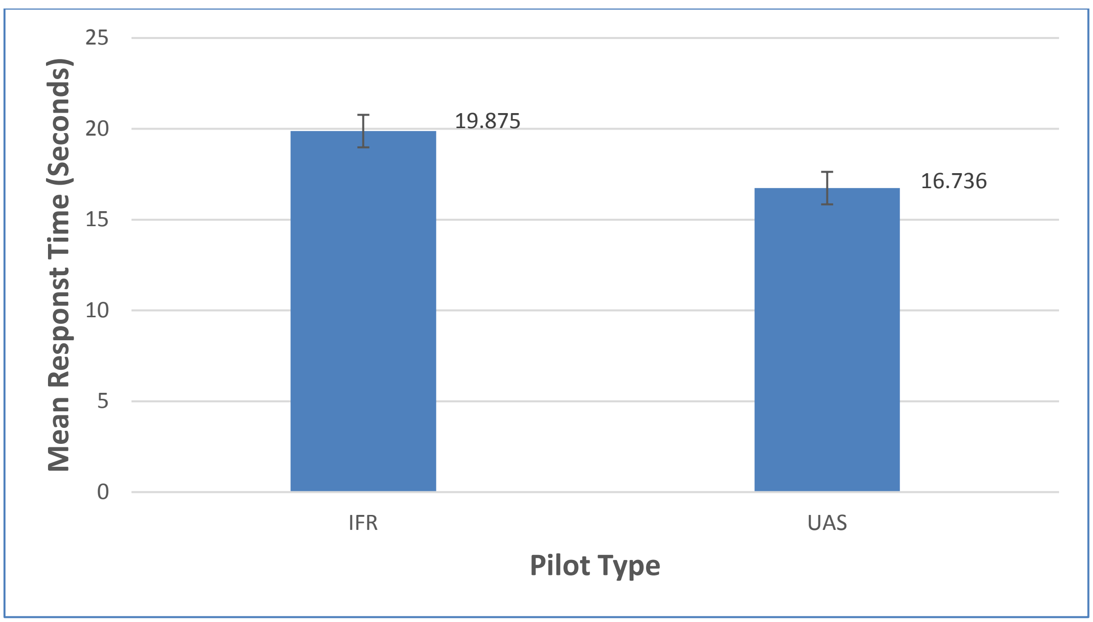


**Figure 9**. Effect of pilot type on mean response time.

Factors affecting response time will be presented in the discussion section. However, age and control station familiarity likely play a key role.

## Interacting with Air Traffic Control

Electrical problems with the voice recording system led to a number of missing voice recordings. For 300 of the trials, the voice recording was not available. Before beginning the experimental trials, participants were instructed that their aircraft was on an instrument flight plan and that, if they had time, they were to contact ATC before departing from the flight plan. They were further instructed that if they did not have time to contact ATC before departing from the flight plan, they were to perform the avoidance maneuver and then contact ATC to inform them of the maneuver.

Based on the 708 recordings available, we found that, for the majority of trials (496, 70%), pilots would first maneuver the aircraft and then contact ATC afterward. ATC was contacted prior to maneuvering for 183 (26%) trials and no contact was made for 29 (4%) trials. Of the 29 trials where no ATC contact was made, 24 were by manned aircraft pilots and 5 were from unmanned pilots. Whether the pilots maneuvered before ATC contact or after did not make a large difference in the overall pilot response time. The mean response time when maneuvering before contacting ATC was 16.92 seconds. The mean response time when contacting ATC before maneuvering was 18.75 seconds, which was less than 2 seconds different. Because of the large number of missing trials, we did not perform any inferential statistics on the ATC interaction data.

# DISCUSSION

In this paper, three types of data were analyzed that were collected as part of the study that was reported in Williams et al. (2017). These data types were avoidance maneuver selections, maneuver response times, and ATC interaction during traffic avoidance activities. Because of the large number of missing voice recordings, we were unable to fully analyze the ATC interaction data. However, it was clear from the available data that, for most of the trials, pilots elected to maneuver first before contacting ATC. This was true whether the level of alert elevated to a warning or not. Interestingly, the percentage of encounters where maneuvers preceded ATC contact was lower for warnings (68%) than it was for cautions (85%). One possible explanation for this finding is that, because the pilots were maneuvering more quickly, a larger percentage of the encounters did not escalate to a warning condition.

Whether ATC was contacted before or after the maneuver made little difference in the overall response time of the pilot to begin the avoidance maneuver (16.92 vs. 18.75 seconds, before vs. after ATC contact). Beyond these observations, there is very little empirical support to reach further conclusions. Other questions, such as whether contacting ATC first made any difference on the likelihood of violating well clear, or if there were problems caused by a change in alert status during contact with ATC, will have to wait for other studies. The focus of the rest of the discussion will be on the maneuver and response time data.

## Avoidance Maneuvers

It is interesting to note that there was a significant difference in maneuver selection bias due to display type in this study. It is easy to suggest that these differences are due to how both the banding and blob displays tend to focus attention on horizontal maneuvers. However, this result contrasts with NASA studies looking at similar displays that found no difference in maneuver preference due to display type (Rorie, Shively, Fern, Santiago, Consiglio, & Mueller, 2015; Rorie, Fern, Shively, & Santiago, 2016). One change from the NASA studies and this study was that the NASA research used UAS pilots only while our study used both manned and unmanned aircraft pilots. NASA's Part Task 5 HITL (Rorie, Shively, et al., 2015), which used only Predator pilots, found a strong bias for horizontal maneuvers across all their displays ranging from 85% for their information-only display to 92% for their banding display. Whether this strong bias was due to Predator training is uncertain. NASA's Part Task 6 HITL (Rorie, Fern, Shively, & Santiago, 2016), which used a mixture of Global Hawk and Predator pilots, saw horizontal maneuvers selected 61% of the time. However, the UAS pilots in our study did not exhibit as strong a bias for horizontal maneuvers as those in the NASA studies. While they did maneuver horizontally more often than the manned aircraft pilots (51% vs. 48%), this difference was not statistically significant. Furthermore, unlike the NASA studies, both the manned and unmanned pilots showed a bias for vertical maneuvers while using the baseline display (manned 65%, unmanned 54%). While it is likely that training had some effect on maneuver preferences, other factors related to training could have modified the overall maneuver decisions.

Another difference between the NASA studies and the current research was the use of two different pilot user interfaces from the one employed in the NASA research. The NASA studies used a control station simulation developed by the Air Force Research Laboratory at Wright-Patterson Air Force Base in Dayton, Ohio called Vigilant Spirit. Inputting maneuver commands using the Vigilant Spirit required a different procedure than both the Predator and ICOMC2 stations used in our study and this may have influenced maneuver selection as well. Even though we do not have direct evidence to support this assumption, the large differences in maneuver biases across different studies invites speculation and requires further research.

Besides the effect of display type on maneuver preferences, evidence was also found that encounter geometry played a significant role. Some of the encounter geometries elicited a significantly large portion of avoidance maneuvers along a single dimension, either vertical or horizontal. This statement was confirmed statistically using a chi-square analysis. In analyzing what aspects of the encounter geometries were most important, we can make the following two observations.

**Having ownship descending at the time of the encounter tended to elicit a vertical avoidance maneuver**. Kuffner et al. (2016) reported results from a survey of 23 UAS pilots regarding avoidance maneuver decisions. The majority of the surveyed pilots reported that if they were encountering traffic while climbing or descending, their preference would be to level off (vertical maneuver) to avoid a conflict. The current research showed support for this when it was found that, of the three conflict scenarios where the number of vertical avoidance maneuvers was greater than the number of horizontal maneuvers, two of the scenarios occurred when ownship was descending. There were no other scenarios where ownship was maneuvering vertically.

**Having the intruder maneuvering vertically at the time of the encounter tended to elicit a horizontal maneuver**. Both of the scenarios eliciting the largest percentage of horizontal maneuvers (2OV 84%, 3CV 64%) involved an intruder that was maneuvering vertically. In the first scenario, 2OV, the intruder was overtaking ownship from directly behind and was climbing. In the second scenario, 3CV, the intruder was crossing the path of ownship while descending. It seems possible that the lower level of horizontal maneuvers in the second scenario relative to the first is due to the crossing maneuver of the intruder making a horizontal maneuver less safe relative to the overtake scenario. Regardless, the finding of more horizontal maneuvering being associated with a vertically maneuvering intruder conflicts somewhat with the Thomas and Wickens (2008) finding that increased vertical maneuvering was limited to when the intruder was ascending from below or descending from above. However, their finding also occurred under increased time pressure. We also found some evidence that increased time pressure led to more vertical maneuvering, as was discussed in the results section.

Referring back to the maneuver preferences summarized from manned pilot studies (Guendel et al., 2017), we can draw the following conclusions. First, the current study found evidence supporting a preference for single-axis maneuvers over multi-axis maneuvers, although the percentage of multi-axis maneuvers found in the current study (25%) was higher than those found in the NASA studies (PT5, 4%; PT6, 7%) and by Kuffner et al. (2016) (approx. 10%).

Second, we did not find a general preference for vertical maneuvers - only with the baseline and CPA displays. Both the Blob and Banding displays elicited a preference for horizontal maneuvers. Finally, as expected, we found little preference for airspeed maneuvers.

**Maneuver Response Time**

As with the data analyzed in Williams et al. (2017), the response time results reported here provide further support for the superiority of both the blob and banding displays relative to the baseline display configuration. This support comes from the finding of a significant decrease in maneuver response time with both the blob and banding displays when compared to the baseline display. In addition, pilots responded faster in the blob and banding displays regardless of pilot type or control station. Although, it was noted that response times in the Predator control station were significantly faster than the ICOMC2 station across condition for both pilot types, and that UAS pilots maneuvered significantly faster than manned aircraft pilots. As with Williams et al. (2017), the results provide further confirmation for the decision to include suggestive maneuver information in the RTCA SC-228 DAA minimum operational performance standards.

The overall response times found in the current study were very close to the response times reported for the NASA Part Task 5 HITL (Rorie, Shively, et al., 2015). In that study, NASA researchers looked at two different banding displays (Stratway+ and Omni Bands). Response time to the Stratway+ display averaged 18.78 seconds and to the Omni Bands averaged 20.9 seconds. Response time to the banding display in our study was 17.61 seconds.

In addition to the significant effect of display type on pilot response time, we also found significant effects of both pilot type and control station type on response time as well. The UAS pilots in our study responded significantly faster to the traffic alerts than the manned aircraft pilots (16.74 vs. 19.88 seconds). Part of this difference may have been due to the UAS Predator pilots having more familiarity with the control interface than the manned pilots, but part might be due to differences in age between the UAS and manned aircraft pilots. Regardless, the effect of pilot type did not interact with the display type effects in the study.

Pilots using the Predator control station had an almost 5 second advantage over those using the ICOMC2 station (16.05 vs. 20.88 seconds). Even though the Predator station had a more complex interface than the ICOMC2 station, the actual inputting of the commands took longer with the ICOMC2 station. However, it should be noted that the measurement of pilot response time included the initial maneuvering of the aircraft. Because the Integrator aircraft controlled by the ICOMC2 station was slower than the Predator, this could have had some impact on the increased measured response time. Additionally, this difference in response time did not result in a significant difference in either the number of well clear violations across the two interfaces or the severity of the well clear violations (Williams et al., 2017).

## CONCLUSIONS

Constructing a model of pilot avoidance maneuver tendencies cannot be an exact science. Studies have shown that the selection of an avoidance maneuver can be influenced by a large number of factors, including training, the types of traffic information that are displayed and the manner in which it is displayed, the control interface being used, conflict geometry, and even the habits of an operator. The finding that display type had a significant effect on maneuver tendencies in the current study but not in other studies suggests that the effect of display type can be overwhelmed by other factors. What is likely needed to construct a more accurate model of pilot maneuver tendencies is a weighting of those factors that influence the maneuver decision and an understanding of which aspects of a certain factor influence the weighting.

For example, a particular control interface design might promote horizontal maneuvers over vertical by making the inputting of a horizontal maneuver less complex than a vertical maneuver. We still need to understand how much of a difference in complexity there needs to be before control interface design becomes more important than training or display symbology or some other factor.

Accomplishing this task would require a systematic comparison of specific factors and an assumption that other factors not included would not interact with those being tested. The feasibility of this approach is questionable. The best approach at this time for modeling pilot maneuver tendencies is to weight vertical and horizontal maneuver bias equally, with a much smaller tendency for speed changes.

The maneuver response time data lends additional support to the use of suggestive maneuver information as part of the minimum information requirements for DAA traffic displays. Again, as was the case with well clear violation data reported in Williams et al. (2017), support was found for both the banding and blob displays. We believe that enough support has been found to consider inclusion of the blob symbology as a substitute for the banding symbology for these displays and would like to see future versions of the RTCA SC-228 DAA MOPS include this display symbology as well.

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