AIAA AVIATION Forum
12-16 June 2023, San Diego, CA and Online
AIAA AVIATION 2023 Forum
10.2514/6.2023-3683

Helicopter Pilot Assessments of the Airborne Collision Avoidance System X_R with Automated Maneuvering

Casey L. Smith[1], R. Conrad Rorie[1], Meghan Chandarana[2], Terence L. Tyson[1], and Jillian N. Keeler[1]
NASA Ames Research Center, Moffett Field, CA, 94035, USA

Vivian Tran[3]
California State University, Long Beach, Long Beach, CA 90840 USA

The Airborne Collision Avoidance System X (ACAS X) is a next-generation collision avoidance tool developed to support different aircraft types and operations. The rotorcraft variant – referred to as ACAS X_R – is designed to accommodate existing helicopter platforms as well as in-development, electric vertical takeoff and landing (eVTOL) models, which are critical to the emerging concept of operations referred to as Advanced Air Mobility. The fundamental role of ACAS X_R is to provide Detect and Avoid (DAA) and/or Collision Avoidance (CA) protection against airborne traffic. DAA alerting and guidance in the context of ACAS X_R is caution-level and "suggestive," and is to be used by the pilot if, and when, they decide to maneuver against an identified threat to DAA "well clear." The CA alerting, by contrast, is warning-level and "directive," with the pilot required to comply with the associated guidance to prevent a predicted Near Midair Collision (NMAC). The CA alerts generated by ACAS X_R are referred to as Resolution Advisories (RAs) consistent with previous CA systems. Unlike earlier CA systems, ACAS X_R issues RAs in the horizontal and vertical dimensions as well as multi-axis RAs (referred to as "Blended" RAs). The current study was a human-in-the-loop simulation that presented helicopter pilots with ACAS X_R alerts and guidance in a fixed-base eVTOL simulator with varying levels of automation. Objective results showed that pilots complied with all RAs within the expected 5-second time window and responded to DAA alerts quicker than in earlier studies with ACAS X_U. No NMACs occurred, and losses of well clear were mainly attributed to the obligation of the pilots and system to maneuver only after the CA phase of the encounter had begun. Objective performance did not vary as a function of the automation variable. Non-compliance with RAs most frequently occurred when pilots determined they were too close to the terrain to continue to follow Descend RAs, performing vertical maneuvers instead of following Horizontal RAs, or rejecting Horizontal RA updates because they felt that enough maneuvering had been performed. Subjectively, pilots found the DAA and RA alerting and guidance intuitive and useful for VFR helicopter operations. Slightly more pilots preferred the Automated RA condition to the Manual RA condition. Caveats and future implications are discussed.

I. Introduction

As plans to increase the density and complexity of urban airspace progress, so do the techniques and technologies that will be used to keep airways safe. Advanced Air Mobility (AAM) targets these concerns by examining emerging markets set to produce new types of aircraft and airspace operations. AAM aircraft may be used for passenger or cargo

[1] Research AST, Human Systems Integration Division, MS262-2.
[2] AST, Intelligent Systems Division, MS269-x.
[3] Graduate Student, Department of Psychology, 1250 Bellflower Boulevard.

transport and are expected to perform flights that are shorter in duration and occur over rural and urban environments. These vehicles and operations necessitate the exploration of novel types of energy sources, propulsions, noise mitigations, aerodynamic models, and safety systems [1]. In these new UAM environments, strategic deconfliction will be the responsibility of automated flight rules and air traffic management systems like Providers of Services for UAM (PSUs); tactical deconfliction will be the responsibility of the operators and air traffic control (ATC) [2].

Like current-day pilots, AAM operators will be responsible for maintaining well clear and/or avoiding collision hazards, regardless of usage, configuration, or communication modality. Avoiding losses of well clear and collision hazards has traditionally been achieved through ‘see and avoid’ (SAA), which requires pilots to maintain vigilance, visually acquire, and, as necessary, deconflict with other aircraft when flying under both Instrument Flight Rules (IFR) and Visual Flight Rules (VFR) [3]. The Air Traffic Management (ATM) system was introduced in the 1920s due to the human-centered and environment-centered limitations of SAA alone [4–6], and it was immediately beneficial in enhancing safety by supporting pilots through aircraft detection and traffic separation in the National Airspace System (NAS) through the mid-1900s [7]. Starting in the 1980s, the Traffic Alert and Collision Avoidance System (TCAS I/II) was developed to provide an additional layer of protection against midair collisions [8]. This Collision Avoidance (CA) function alerted pilots to nearby traffic and was capable of issuing vertical commands (e.g., "Climb, Climb") that were predicted to increase separation between aircraft.

More recently, a Next Generation upgrade of TCAS II has been underway. Referred to as the Airborne Collision Avoidance System X (ACAS X), this system differs significantly from TCAS II. ACAS X accommodates radar and electro-optical sensors instead of beacon-only surveillance. ACAS X also has different collision avoidance logic from TCAS II and has been designed to adapt to specific aircraft types, reduce unnecessary advisories, and improve its general level of safety [9]. Also unique to some variants of ACAS X is the inclusion of Detect and Avoid (DAA) logic. Originally designed for uncrewed aircraft, DAA utilizes the available surveillance sources to provide remote pilots with increased situational awareness by issuing visual and aural alerts that are intended to maintain DAA Well Clear (DWC), occurring before the issuance of CA alerting and guidance [10, 11].

The variants of ACAS X that include DAA functionality, in addition to the CA functionality, are ACAS X_U (designed for larger uncrewed vehicle configurations), $_{S}X_U$ (designed for smaller uncrewed vehicle configurations), and ACAS X_R (designed for both crewed and uncrewed rotorcraft configurations). The DAA alerting and guidance issued by ACAS X is caution-level, suggestive (i.e., does not command a specific avoidance maneuver), and triggers approximately 90 seconds from the closest point of approach (CPA). The current definition of DWC is 4,000 ft horizontal and 450 ft vertical separation with approximately 35 seconds of extra time (i.e., 35-second Tau) to CPA. By comparison, CA alerting is warning-level, directive (i.e., commands specific maneuvers), and triggers approximately 30 seconds from CPA. TCAS II and ACAS X both refer to CA alerting and guidance as Resolution Advisories (RAs), which are intended to prevent Near Midair Collisions (NMACs), defined as 500 ft horizontally and 100 ft vertically. According to the Minimum Operational Performance Standards (MOPS) for DAA systems, DAA alerts always assume that pilots will respond manually, but RAs may be optionally automated to reduce the time taken to comply with the commanded guidance [12]. Unlike TCAS II, which only issues advisories in the vertical dimension, certain ACAS X variants can also issue advisories in the horizontal dimension, as well as advisories in both dimensions simultaneously (referred to as Blended RAs). All types of RAs update as traffic conflicts progress, meaning the guidance ACAS X provides can change over the course of an encounter.

Previous research has investigated the performance of remote pilots when using the DAA and CA guidance generated by ACAS X_U [10, 11]. These earlier studies found that pilots lost well clear more often than had been seen with other DAA systems, but that ACAS X_U led to less severe losses of separation due to the use of directive RA guidance. Pilots generally found X_U to be useful but noted a tendency for Horizontal RAs to update too often. Prior research has also studied how ACAS X_U RAs may be automated, albeit without the ACAS X_U logic integrated into the ground control station. That research found that pilots preferred greater visual salience when automation was engaged, aural alerts to indicate when automation had assumed control, and a simple disengagement of automation (e.g., only moving the inceptor instead of undergoing a multi-stage process) [13].

The current study investigated the use of ACAS X_R in a crewed, AAM vehicle configuration with experienced helicopter pilots as participants. The participants flew enroute traffic conflict scenarios in a fixed-base electric vertical takeoff and landing (eVTOL) simulator. The conditions of the study were varied whether the RAs, and subsequent return to course maneuvers, were automated and whether or not the pilots responded to just the RAs or also responded to the DAA alerting. The effect of the automation condition on pilot performance and subjective ratings of the system will be discussed. Pilots’ use and perception of the DAA guidance—which has not previously been investigated with ACAS X in a crewed configuration—will also be covered. This study was approved by the NASA Institutional Review Board, and was performed in support of NASA's AAM project, under the Automated Flight and Contingency

Management (AFCM) sub-project. It serves as the first in a series of studies that investigate ACAS X_R in the context of AAM operations.

II. Method

A. Participants

Helicopter pilots were recruited for the current study due to their familiarity with flying at low altitudes and in the same types of environments envisioned under AAM. A total of 12 pilots with private helicopter licenses (M_{age} = 56, all were male) were recruited. Participants were a combination of civilian and military-trained and had an average of 1,500 civilian flight hours with helicopters. All participants had familiarity with flight simulators. Most had experience with nap-of-the-earth missions, and half were familiar with TCAS II.

B. Vehicle Models

NASA's Lift Plus Cruise (LPC), eVTOL model was used for the ownship aircraft. This model was developed by the Revolutionary Vertical Lift Technologies (RVLT) project and continues to be advanced at NASA Ames Research Center (ARC) [1, 14]. For the current human-in-the-loop (HITL) simulation, the aircraft was configured to fly at 120 knots true airspeed (KTAS), with a default turn rate of 3°/sec and a default vertical rate of 1,000 ft/min. The only other traffic the ownship encountered in the airspace were scripted intruders. A Cessna vehicle model was used for all intruders, which were designed to mimic general aviation aircraft. They were configured to fly at either 100 or 160 KTAS, with the same default turn and vertical rates as the LPC model.

C. Simulation Environment

Pilots flew in a fixed-base flight simulator in the Human Autonomy Teaming Laboratory at NASA ARC. FlightDeckZ (FDz) served as the aircraft simulation software for both ownship and intruder aircraft [15, 16]. All aircraft flew within the San Francisco Bay Area under VFR and visual meteorological conditions (VMC). The ownship and the simulated intruder aircraft were initialized at mission altitude and established on a pre-defined collision course. The ownship started with the autopilot engaged (via heading, speed, and altitude holds). There was no additional background traffic or interactions with ATC or PSUs. Upon completion of each run, the ownship was reset and reinitialized at the appropriate positions and altitudes for the next scripted encounter.

D. Displays and Controls

Examples of the displays and controls are shown in Fig. 1, and an example of a pilot seated in front of the controls is shown in Fig. 2. Control of the aircraft was achieved using a right-side inceptor and a Mode Control Panel. The inceptor allowed pilots to increase left and right bank angles (i.e., turn left and right) as well as increase and decrease vertical rates (i.e., climb and descend). A left inceptor was provided in the cockpit for increasing and decreasing speed; pilots were trained not to use the left inceptor to avoid disrupting the timing of the scripted encounters. Rudders were absent, and slip control was automatically generated for each turn. The Mode Control Panel was a touchscreen monitor that allowed pilots to zoom in/out and select north-up/track-up views on the navigation display (ND); it also provided buttons for the pilots to manually toggle the autopilot and the auto-maneuvering functionality on/off.

Pilots monitored the flight environment through three out-of-window screens (synthetic weather, terrain, and obstacles provided by X-Plane) and one Electronic Flight Display. The display provided inceptor-position indicators, a Primary Flight Display (PFD), and an ND. The PFD showed ownship's airspeed, heading, altitude, vertical speed, and relative positions (i.e., pitch and bank). The ND showed ownship's airspeed, heading, altitude, position, and the positions, directions, and alert level of surrounding traffic. Guidance issued by ACAS was displayed on both the PFD and ND.

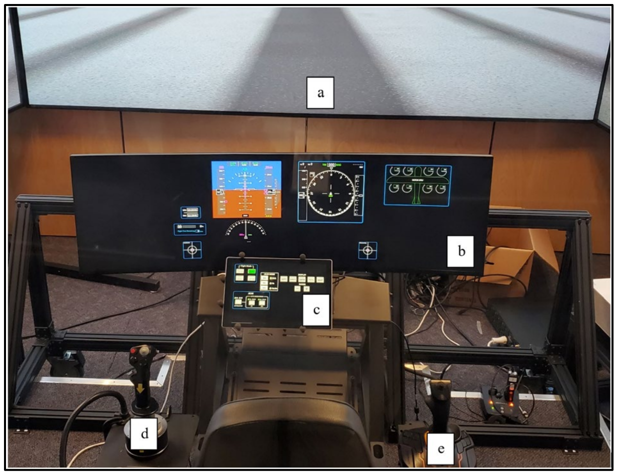


Fig. 1 Pilot displays and controls: (a) Out-of-window views, (b) Electronic Flight Displays, (c) Mode Control Panel, (d) Left inceptor, (e) Right inceptor.

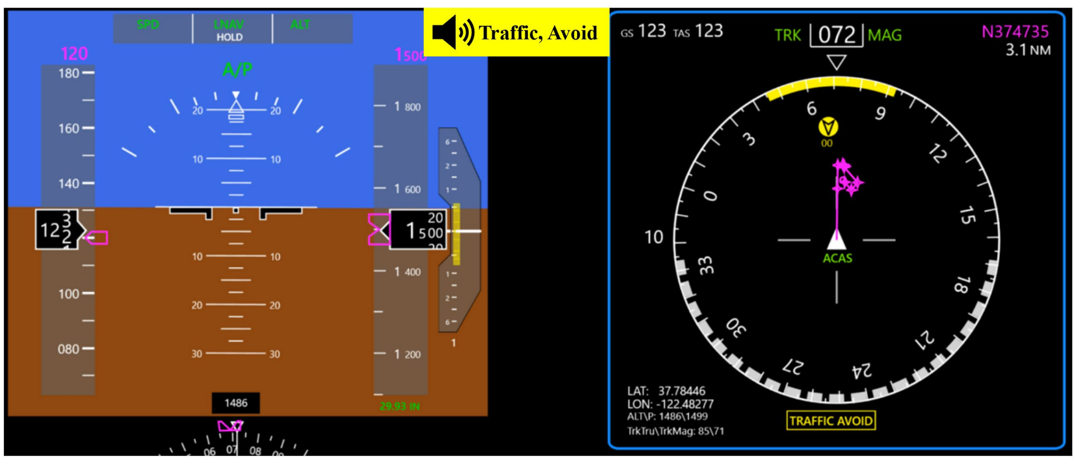
Fig. 2 Cockpit configuration for the current study. The pilot is situated in front of the controls.

E. Detect and Avoid System

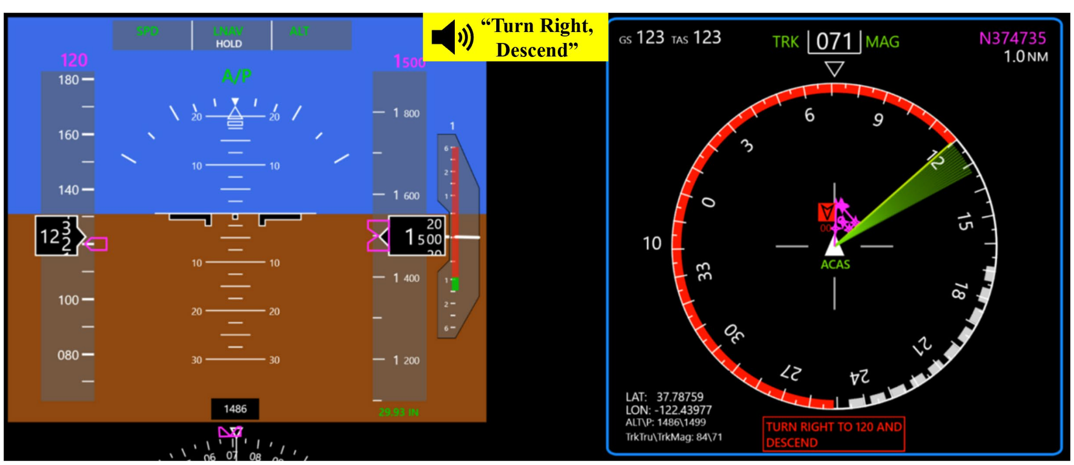
Alerting and guidance against scripted traffic were provided by ACAS X_R. Alerts were issued as a combination of guidance banding, traffic symbol changes, text banners, and aural cues. Alert type was determined by the predicted time to, and separation distance at, CPA. Table 1 shows examples of intruder icons and the corresponding expected pilot response. Figs. 3a and 3b show examples of banding and other display elements of a DAA and RA alert. Default traffic was displayed in cyan. DAA alerts were caution-level (i.e., yellow) and nominally preceded any RAs. DAA alerts could be either Preventive or Corrective, with Corrective alerts requiring evasive action to maintain DWC. DAA guidance was provided in the form of heading and vertical speed banding, which indicated the headings and/or vertical speeds to avoid to prevent a loss of DWC (Fig. 3a). If DWC could not be maintained, an RA would be issued to cue the pilot to take immediate action to avoid an NMAC. RAs were warning-level (i.e., red) and commanded specific maneuver type(s) (Fig. 3b). Three general types of RAs were issued by ACAS X_R: Horizontal RAs, which command a target heading, Vertical RAs, which command a target vertical speed, and Blended RAs, which command both simultaneously. The RA guidance was depicted via red arcs (indicating headings and/or vertical speeds to avoid) and green bands (indicating headings and/or vertical speeds to achieve). ACAS X_R assumed pilots would comply with RAs within 5 seconds, and that they would achieve the commanded Horizontal RAs with a standard rate turn (3°/sec) and the Vertical RAs with a vertical rate of +/- 1,000 fpm. During the progression of an encounter, RAs could be updated in a number of ways. An individual RA could be reversed (e.g., from "Turn Left" to "Turn Right") or strengthened (e.g., from "Climb" to "Increase Climb"), and the other dimension could be added at any point to transform the RA from single to blended. The target headings associated with the Horizontal RAs were frequently updated over the course of a single RA encounter to ensure the pilot continued their turn as they neared the commanded heading.

Symbol	Name	Pilot Action	Aural Alert Verbiage
	Resolution Advisory (RA)	• ***Immediate action required to comply with RA*** • Must maneuver within 5 seconds	"Climb/Descend" x2 "Turn Left/Right" x2 or a combination of above
	Corrective DAA Alert	• **Action required to remain 'DAA well clear'**	"Traffic, Avoid"
	Preventive DAA Alert	• **No action required to remain 'DAA well clear'** • Not currently a threat; monitor for potential increase in threat level	"Traffic, Monitor"
	Guidance Traffic	• **No action required to remain 'DAA well clear'** • Ownship maneuvers against traffic might generate increase in threat level	N/A
	"Other"	• **No action required to remain 'DAA well clear'** • No coordination required	N/A

Table. 1 ACAS X_R alerting structure.



(a)



(b)

Fig. 3 (a) Example of an active DAA Corrective alert (yellow bands, icon, and banner with aural cue), (b) Example of an active Resolution Advisory (red bands, icon, and banner with aural cue and green target indicator).

III. Experiment Design

Before data collection, pilots received one hour of classroom-style instruction on the simulator, behaviors of the ACAS X_R system, and aspects of the experimental conditions they will experience. They were also led through four, approximately 20-minute, hands-on sessions with the simulator: one introduction and handling session and three sessions to familiarize them with each experimental condition before its corresponding data collection. Each session included three training scenarios that explored horizontal, vertical, and blended alerts. The times for hands-on sessions varied between pilots because each pilot was allowed to train until he felt comfortable with the aircraft, DAA system, and experimental condition.

During data collection, pilots completed one trial per experimental condition, with 10 encounters flown per trial. Each encounter lasted approximately five minutes, resulting in ~50 minutes per trial and ~2.5 hours for data collection. Ten unique RA-only encounters and ten unique DAA encounters were created. The RA encounters were designed to generate a roughly even distribution of horizontal, vertical, and Blended RAs. The DAA encounters were similarly designed to result in a variety of pilot responses. The ten unique RA-only encounters were randomized and used to generate two separate encounter sets, which differed in the order of presentation of each specific encounter. The Manual and Auto RA conditions were then counterbalanced against those two different RA encounter sets. Only one encounter set was created for the DAA encounters since there was only one DAA condition per participant. Encounters presented pilots with a traffic conflict mitigated by the automation, the human pilot, or a combination of both. Variables of interest to this study were the types of encounters and levels of automation present during a given trial, which are detailed further below.

A. Encounters

1. Resolution Advisory Encounters

For these encounters, pilots were trained to disregard DAA alerting and guidance and delay any maneuvers until ACAS issued the RA alert. This was done to keep pilots from preventing RAs entirely by maneuvering as soon as the DAA alerting appeared. At the onset of the RA, pilots were instructed to comply, or ensure the system complied, with the command maneuvers within five seconds, depending on the automation condition. A return to course (RTC) maneuver was also performed by the pilot and/or the system, depending on the level of automation, before the encounter was considered complete. Pilots were instructed to comply with the RA unless they determined it to be a safety risk for the aircraft.

2. Detect and Avoid Encounters

The DAA encounters were always presented at the end of the day and were considered separately from the RA encounters. The DAA encounters were not counterbalanced with the RA encounters to avoid confusion as to whether or not participants were supposed to respond to the DAA alerting and guidance. Pilots were trained to disengage the autopilot and respond as soon as a DAA Corrective alert was issued and to manually comply with RAs if they happened to be issued, despite their maneuvering for the DAA alert. The RTC maneuver was always performed manually after the conflict had been cleared. These DAA encounters, as well as any RAs that were issued during these trials, were analyzed separately from the RA encounters.

B. Levels of Automation

Levels of automation were explored during the RA encounters exclusively. Because of this, pilots did not respond to initial DAA alerting/guidance, and they therefore waited until the onset of automatic RAs before other manual maneuvers were allowed.

1. Automated RA (Auto RA) Condition

The automated RA and RTC functions were enabled by default in this condition. Pilots monitored the system as it automatically responded to RA guidance in accordance with ACAS's performance assumptions and within one second of the alert. Pilots had the ability to disengage the auto-maneuvering function if they felt that this was necessary. Automation could be overridden at any point by deflecting the right inceptor. Pilots could re-engage the automatic RA response while an RA was still active, if desired, by pressing the dedicated Auto RA button. If the pilot did not disengage the RA's automatic response, the RTC maneuver would also be executed automatically. Like the automated RA maneuvers, pilots were told to monitor the system as it returned to course but had the ability to disengage the automation at their discretion. It should be noted that the automatic RA and RTC functions are not inherent to ACAS X_R. Software was developed to translate the RA commands, which were output by ACAS X_R, into the appropriate turn and climb/descend maneuvers that the FDz simulator software could interpret. Furthermore, whereas the automatic-RA maneuvers were designed to conform to the specific advisories generated by ACAS X_R, the auto-RTC behavior was based on much simpler logic. The auto-RTC logic first looked for receipt of the clear of conflict message from ACAS and then returned the aircraft to autopilot mode (which would fly to the previously established waypoint and altitude) once there was no DAA banding present on the display, plus a five-second buffer, to decrease the chances of re-engaging a traffic conflict.

2. Manual RA Condition

The automated RA and RTC functions were fully disabled in this condition and could not be enabled by pilots during these runs. Pilots manually responded to RAs by using the right inceptor to achieve the indicated target heading and/or target vertical speed. Training included ACAS performance assumptions (3°/second turn rates and +/- 1,000 ft/minute climb/descend rates); however, the vehicle could exceed those rates if the pilot chose to maneuver more expediently. Pilots executed the RTC maneuver by manually flying back to course or re-engaging the autopilot (or a combination of both).

IV. Metrics and Analyses

A. Objective Data

Objective data were collected using output logs from ACAS X_R, which recorded the timing of all alerts and the positions of ownship and intruders. Screen recordings of the Electronic Flight Displays were also captured for all encounters, allowing researchers to code and extract additional and contextual information.

1. RA Types

Refers to the types of RAs (Horizontal, Vertical, and Blended) issued over the course of the current study.

2. Losses of DAA Well Clear (LoDWC)

Refers to the proportion of encounters that resulted in an intruder penetrating the DAA well clear threshold (defined as 4,000 feet horizontally, 450 feet vertically, and 35 seconds modified Tau). Also includes "High-Severity" losses of DAA well clear (4,000 feet horizontally and 450 feet vertically; excludes the modified Tau component).

3. Near Midair Collisions (NMAC)

Refers to the proportion of encounters that resulted in NMACs (defined as 500 feet horizontally and 100 feet vertically).

4. Manual Response Times

Refers to the time elapsed (in seconds) from the onset of DAA Corrective alerts or RAs (in the manual condition) and the pilot beginning their corresponding maneuver.

5. Maneuver Characteristics

Refers to the size of the maneuver for horizontal deviations (measured as magnitude of heading change) and vertical deviation (measured in feet between initial and final altitude). Also includes the time from the onset of the conflict and the start of the RTC maneuver.

6. Automation Disengagement

Refers to the number of cases where pilots disengaged the automated RA or RTC functionality in the Auto RA condition.

7. Compliance with Resolution Advisories

Refers to whether or not the pilot successfully complied with the RA guidance (i.e., continued to climb/descend/turn for as long as the corresponding RA was active). Examples of non-compliance include pilots leveling-out of a descent while a Descend RA is still active and executing a climb rather than right turn following a right-turn Horizontal RA.

B. Subjective Data

Subjective data were collected from questionnaires provided to the pilot after each encounter (30 total), each trial (three total), and a full day in the simulator. The questionnaires presented combinations of multiple choice, visual analog scales, and open-ended questions. The final post-simulation questionnaire was also followed by a debrief that allowed the pilots to elaborate on the information provided in the questionnaires, elicited additional information, and finalized the day. A subset of the collected subjective data includes pilot feedback regarding the following elements of the study:

1. Acceptability of ACAS X_R Guidance and Presentation

Refers to pilot ratings regarding the display of DAA/RA alerts and guidance as well as display of automation information.

2. Acceptability and Presentation of Automated RA & RTC Maneuvers

Refers to pilot ratings regarding the safety and effectiveness of the system's automated maneuvers.

3. Perceived Workload

Refers to pilot workload ratings using NASA's Task Load Index (NASA TLX), which are chosen for six dimensions: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration [17].

4. Perception of Overall Simulation Experience

Refers to pilot ratings regarding vehicle handling and the overall fidelity of the simulator.

C. Analyses

Descriptive statistics are provided as comparisons of means and standard errors for objective and subjective data. Manual RA and Auto RA conditions were directly compared. However, DAA corrective alerts were issued much sooner than RAs, had different response-time assumptions, and could not be automated. Therefore, metrics of the DAA condition were not directly comparable to the Manual RA and Auto RA conditions; they were instead collected and provided to characterize pilots' use of the DAA functionality.

V. Results

A. RA Types

Out of the 263 RAs issued in this study in the Manual RA and Auto RA conditions, 176 (67%) were Horizontal-only RAs, 48 (18%) were Vertical-only RAs, and the remaining 39 (15%) were Blended. Of the 39 total Blended RAs, 20 (51%) of them were issued nearly simultaneously (within 2 seconds of one another). Of the remaining Blended RAs, 17 (44%) started first as a Horizontal RA, and 2 (5%) started first as a Vertical RA, before the complementary RA was issued, creating a Blended RA. Out of the 120 total DAA encounters, there was no RA issued in 97 (81%) cases. When the DAA encounters progressed to an RA, a Horizontal RA was issued for 22 (18%), a Blended RA for 1 (1%), and no encounters contained a Vertical RA.

Of 211 Horizontal RAs, the initial target heading was updated a single time in 126 (60%) encounters, updated twice in 68 (32%) encounters, and updated at least three times in 13 (6%) encounters. There was no target heading update in 4 (2%) encounters. The initial target heading commanded an average relative heading change of 63-65°, while the final target heading commanded an average relative heading change of 110-112°.

B. Losses of DAA Well Clear & Near Midair Collisions

Out of the 120 encounters experienced in each condition, those that resulted in a LoDWC were 65 (54%) in the Manual RA condition, 68 (56%) in the Auto RA condition, and 9 (7.5%) in the DAA condition. As shown in Fig. 4 below, the number of encounters that resulted in high-severity LoDWC were 1 (0.8%) in the Manual RA condition, 1 (0.8%) in the Auto RA condition, and 2 (1.7%) in the DAA condition. No NMACs were recorded.

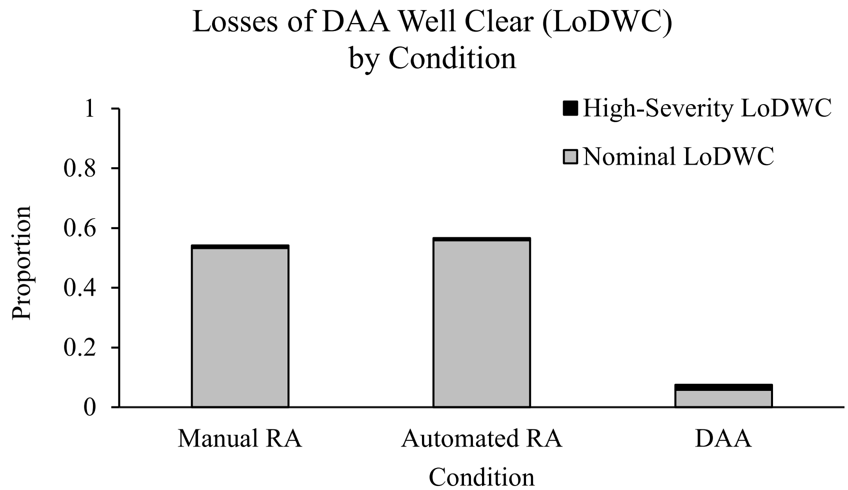


Fig. 4 Nominal Losses of DAA Well Clear (LoDWC) and High-Severity LoDWC by experimental condition.

C. Manual Response Times

Response times in the Manual RA Condition (M = 2.05 s, SE = 0.21 s) were well within the 5-second response time assumption built into ACAS X_R. This held true for pilots' manual responses to all types of RAs. Pilot response times were 1.39 seconds (SE = 0.17 s) on average when responding to Horizontal RAs and 2.71 seconds (SE = 0.29 s) on average when responding to Vertical RAs (Fig. 5). In Fig. 6, the gray and white bars represent the mean response times for horizontal and Vertical RAs, respectively, for specific types of Blended RAs. Simultaneous Blended RAs refer to encounters where the horizontal and Vertical RA components were issued within two seconds of one another. The alternative type of Blended RAs observed in this study consisted of a Horizontal RA followed by a Vertical RA (after more than two seconds). For simultaneous Blended RAs, pilots initiated the horizontal component of the maneuver first (after an average of 1.5 seconds), followed by the vertical component (after approximately 3.5 seconds; see Fig. 6). Response times to DAA alerts in the DAA encounter trials were also found to be under 5 seconds (M = 3.87 s, SE = 0.46 s).

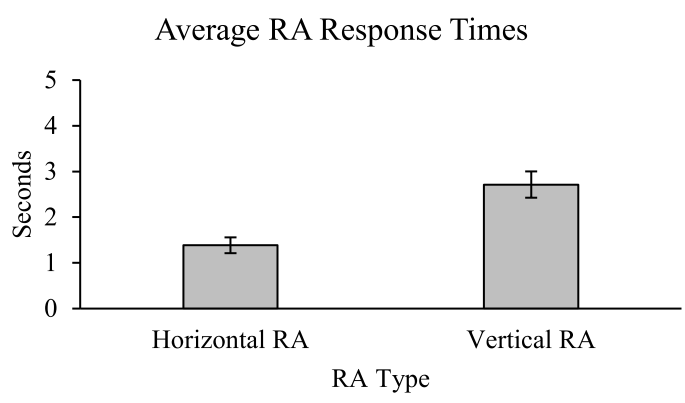


Fig. 5 Pilots' manual response times to Horizontal and Vertical RAs.

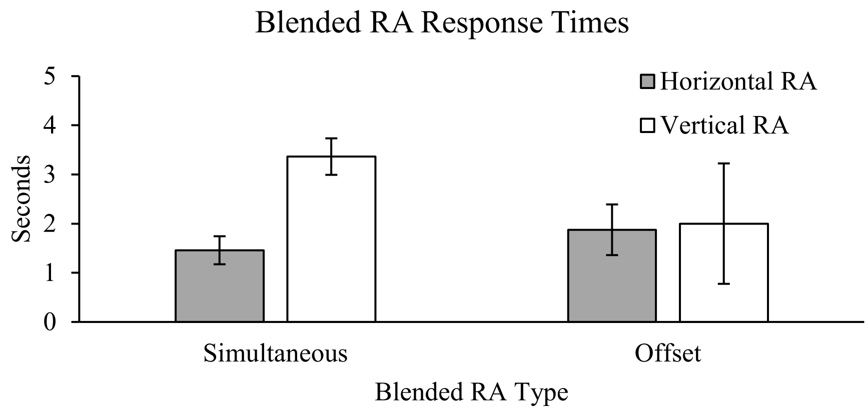


Fig. 6 Pilots' manual response times to Blended RAs during simultaneous (i.e., Horizontal and Vertical RAs occurring at the same time) versus offset (e.g., Horizontal followed by Vertical RAs).

D. Maneuver Characteristics

The size of vertical deviations made during the Manual RA (*M* = 606.00 ft, *SE* = 44.14 ft) and Auto RA conditions (*M* = 631.39 ft, *SE* = 24.98 ft) were highly similar, differing by only 25 feet (4%). The duration of the vertical maneuvers differed slightly more between the Manual RA condition (*M* = 33.57 s, *SE* = 1.48 s) and the Auto RA condition (*M* = 39.57 s, *SE* = 1.85 s), with RAs reaching clear of conflict 6 seconds (15%) faster in the Manual condition. The magnitude of the heading changes made in the Manual RA condition (*M* = 94.97°, *SE* = 2.35°) was approximately 12° (14%) greater than the heading changes made in the Auto RA condition (*M* = 83.22°, *SE* = 3.14°). Conversely, the duration of the horizontal maneuvers was 4 seconds (11%) shorter in the Manual RA condition (*M* = 32.43 s, *SE* = 1.41 s) than in the Auto RA condition (*M* = 36.78 s, *SE* = 0.92 s).

In the DAA condition, pilots' choice of maneuvers was balanced between horizontal-only (40 total, 33%), vertical-only (38 total, 32%), and blended (42 total, 35%). The magnitude of the heading changes made in the DAA condition (*M* = 70.14°, *SE* = 3.18°) was 20° (20%) smaller, on average, than the heading changes observed in the Manual RA condition (95°). The size of the vertical deviations made in the DAA condition (*M* = 526.31 ft, *SE* = 33.55 ft) was 100 ft (13%) smaller, on average, than the vertical deviations made in the Manual RA Condition (606 ft). Average horizontal maneuver sizes and vertical maneuver sizes for each condition are shown in Figs. 7 & 8 below.

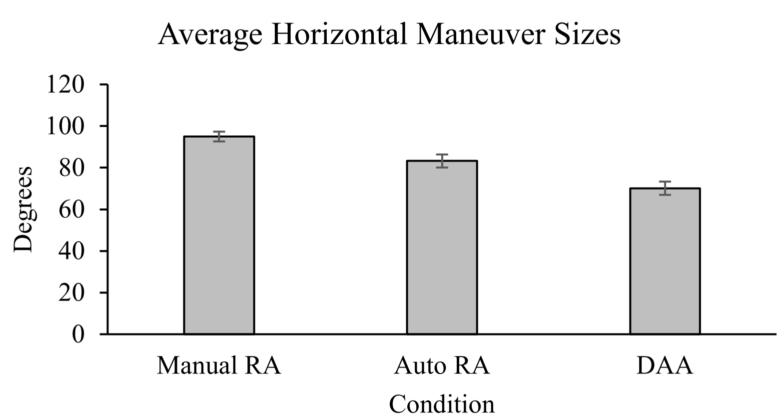


Fig. 7 Average horizontal maneuver sizes for the DAA, Manual RA, and Auto RA conditions.

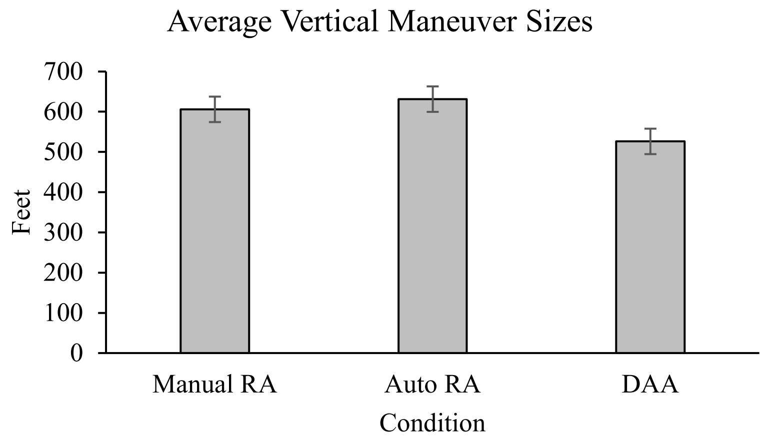


Fig. 8 Average vertical maneuver sizes for the DAA, Manual RA, and Auto RA conditions.

E. Automation Disengagement

Pilots in the Auto RA condition disengaged the automated RA maneuver in 8 (7%) of the 120 scripted encounters. The most common reason for Auto RA disengagement was proximity to terrain. Conversely, pilots disengaged the automated RTC maneuver in 14 (12%) of the 120 scripted encounters. The most common cause of RTC disengagement was so that pilots could avoid re-triggering a conflict with the intruder they had just maneuvered against. This was typically because the autopilot was going to attempt to re-capture the original route by continuing to turn in the direction of the recently-cleared RA by performing a 360° maneuver. In certain encounter geometries, making this 360° turn would place the ownship back on a collision course with the intruder.

F. Compliance with Resolution Advisories

Pilots were found to intentionally contradict 20 total RAs (7.60%) across all conditions. Pilots failed to comply with the RA guidance in 8 (3.04%) of the Manual RA condition encounters, 9 (3.42%) of the Auto RA condition encounters, and 3 (1.14%) of the DAA condition encounters (recall that RAs were possible in the DAA condition if the pilot did not fully resolve the conflict using the DAA guidance). The most reported reason for RA non-compliance, 10 of 20 instances, was due to pilots perceiving that they had maneuvered too close to terrain when following a Descend RA. In these cases, pilots determined it was safer to level out, or in some cases initiate a slight climb, while the Descend RA was still active. In 3 of 20 cases, pilots failed to fully comply with Horizontal RAs by disregarding those that continued to persist or update even after the pilots felt they had maneuvered sufficiently. In another 3 of 20 cases, pilots preferred climbs or descends in response to Horizontal-only RAs. Pilots reported that they felt vertical maneuvers in these cases could more effectively resolve the conflict (e.g., complying with the Horizontal RA would have resulted in the aircraft turning in the same direction as the intruder, prolonging the length of the avoidance maneuver compared to a simple climb/descend). The remaining non-compliance cases were due to pilots returning to course before an RA had cleared (2/20) and ignoring a Vertical RA when it was added to an existing Horizontal RA (2/20).

G. Subjective Data

1. Acceptability of ACAS X_R Guidance and Presentation

When questioned on a 5-point scale (1 = “Strongly Disagree”; 5 = “Strongly Agree”), pilots considered the DAA (M = 4.42, SE = 0.26) and RA (M = 4.46, SE = 0.10) alerting and guidance useful for VFR helicopter operations. As shown in Fig. 9, they specifically rated the ACAS X_R alerting and guidance as effective in helping them resolve traffic conflicts in the Manual RA (M = 4.42, SE = 0.19), Auto RA (M = 4.33, SE = 0.19), and DAA (M = 4.33, SE = 0.19) conditions. They rated the RA alerts as understandable regarding the aural cues (M = 4.83, SE = 0.11), appearance of icons (M = 4.92, SE = 0.29), and guidance—in the horizontal (M = 4.58, SE = 0.215) and vertical (M = 4.75, SE = 0.13) dimensions. Similarly, they found the DAA icons (M = 4.83, SE = 0.11), banding (M = 4.50, SE = 0.15), and aural cues (M = 4.92, SE = 0.08) understandable. However, as declared during the open-ended-question portion of the post-encounter questionnaires, most pilots (9/12) believed that Horizontal RAs lasted too long, updated too often, and/or required larger maneuvers than were necessary or reasonable. Most pilots (8/12) also reported that ACAS overrelied on horizontal maneuvers when climbs or descends would have been quicker and more effective. Most pilots (11/12) reported having to contradict ACAS X_R's vertical guidance due to proximity to terrain.

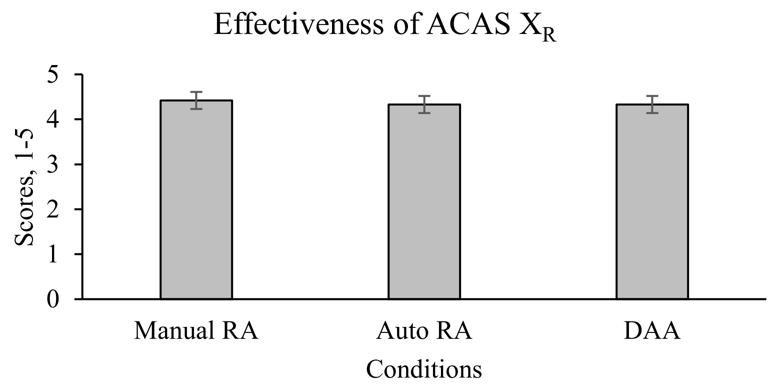


Fig. 9 Pilots ratings regarding the effectiveness of ACAS X_R's alerting and guidance to aid in resolving traffic conflicts.

2. Acceptability and Presentation of Automated RA & RTC Maneuvers

Pilots reported that the system provided sufficient information related to the automatic RA maneuvers made in the Auto RA condition (M = 4.83, SE = 0.11) as well as the automatic return to course maneuvers (M = 4.25, SE = 0.39). Auto RAs were found to be executed effectively (M = 4.00, SE = 0.30), and pilots disagreed that the "overall riskiness associated with the automatic execution of ACAS X_R RAs was high" (M = 2.75, SE = 0.41). However, pilots provided more neutral ratings regarding automated-RTC maneuvers in effectiveness (M = 3.58, SE = 0.29) and riskiness (M = 3.25, SE = 0.25). When given a choice, a slight majority of pilots (7/12) preferred the Auto RA condition over the Manual RA condition.

3. Perceived Workload

For the six workload dimensions of the NASA TLX, the total composite scores are a minimum of six and a maximum of 42 from ratings chosen on the seven-point scale (1 = "Very Low"; 7 = "Very High"). Composite scores were low for the Manual RA (M = 12.42, SE = 1.20), Auto RA (M = 11.50, SE = 1.01), and DAA (M = 11.33, SE = 0.84) conditions, with very little variability between them.

4. Perception of Overall Simulation Experience

Overall, pilots stated they believed they received enough training (M = 5.00, SE = 0.00). They also believed that the controls (M = 4.58, SE = 0.15) and displays (M = 4.83, SE = 0.11) of the simulator were sufficient to test the objectives of the study. Pilots did not find the absence of out-of-window visual traffic troublesome; when asked, "The inability to visually acquire nearby traffic using today's simulator negatively impacted my ability to use the ACAS X_R traffic alerting and guidance system," they reported indifference or disagreement (M = 2.67, SE = 0.36). The version of ACAS X_R utilized in this study did not have terrain or obstacle awareness, but the pilots rated such information as necessary in all conditions: DAA (M = 4.67, SE = 0.26), Manual RAs (M = 4.75, SE = 0.13), and Auto RAs (M = 4.92, SE = 0.08).

VI. Discussion & Conclusion

This study evaluated pilots' interactions with ACAS X_R's alerting and guidance (i.e., banding, traffic symbol changes, text banners, and aural cues) in a fixed-base, eVTOL flight simulator located at NASA ARC. This was accomplished by evaluating the performance of 12 helicopter pilots using the provided displays (i.e., Electronic Flight Display and out-of-window screens) and controls (i.e., right-side inceptor and Mode Control Panel) to maneuver against 30 scripted traffic encounters. The three conditions tested were Manual RA (i.e., pilots only responded to RAs manually), Automated RA (i.e., pilots monitored the system as it performed RAs automatically and intervened if they deemed it necessary), and DAA (i.e., pilots manually responded to the DAA alerting and any subsequent RAs manually). The return-to-course maneuver made after a traffic conflict was performed manually in the Manual RA and DAA conditions but was automated in the Auto RA condition. Output logs, screen recordings, questionnaires, and open-ended debriefs allowed researchers to collect objective and subjective data regarding the effectiveness of ACAS X_R's guidance and how the various information elements were presented to the pilot participants.

When pilots responded *only* to ACAS X_R's RAs (disregarding the DAA alerts and guidance that precede RAs), they were observed to lose DAA well clear (LoDWC) roughly half of the time. However, fewer than 1% of those instances progressed to a "severe" LoDWC (cases where the intruder came within 4000 feet horizontally and 450 feet vertically). Conversely, when pilots were able to respond to the DAA alerting and guidance, their LoDWC rate dropped to 9%, with fewer than 2% progressing to a severe LoDWC. The 9% nominal LoDWC rate is slightly higher than the 5% rate of LoDWC against cooperative intruders that was reported in a previous study with ACAS X_U [10]. On closer evaluation, this increase in LoDWC is likely the result of a simulation artifact for a single encounter in the DAA condition, which had an unusually high descent rate (2,500 ft/min) and afforded pilots little time to maneuver before losing DAA well clear. While the difference in LoDWC rates between the DAA and RA conditions in the current study is hardly surprising, the consistently low rates of severe LoDWC (which was also found in the previous study [10]) highlight the benefit of directive guidance, which prompts quick pilot responses in order to mitigate more serious separation violations, even in cases where the intruder has an extreme vertical rate. In fact, a review of all four severe LoDWC that occurred in this study revealed that they all occurred as a result of pilots attempting to return to course earlier than was appropriate.

In the present study, RAs were automatically executed within 1 second of the advisory being issued in the Automated RA condition. Surprisingly, response times in the Manual RA condition were nearly as fast, with pilots initiating their maneuver an average of 2 seconds after receiving the RA (which is less than 1 second faster than reported in the previous study with remote pilots and ACAS X_U [10]). Pilots tended to initiate horizontal maneuvers about one second faster when the RA was in the horizontal dimension compared to RAs in the vertical dimension. Further, pilots were observed to prioritize horizontal maneuvers over vertical maneuvers when they received simultaneous Blended RAs. These two findings are likely a result of pilots receiving approximately twice as many Horizontal-only RAs than Vertical-only and Blended RAs combined, meaning pilots were primed to respond laterally. This Horizontal RA bias was likely further established by the location of the Vertical RA guidance, which was positioned within the PFD and not collocated with the other alerting and guidance information on the ACAS traffic display. Despite these minor differences, pilots in all conditions were capable of meeting the 5-second RA response time requirement of ACAS X_R (a legacy requirement from TCAS II). It should be noted that the participants experienced these RAs in a simplified airspace environment and were responding to RAs repeatedly and in quick succession. In all likelihood, the response times reported here are the fastest RA response times you can reasonably expect given the control inputs employed in this study. Similarly, the DAA response times captured in this study, which are nearly 14 seconds faster than were reported in [10], see Fig. 10, are the result of pilots using an inceptor, rather than a mouse and keyboard, and not incorporating ATC coordination as part of their DAA maneuver process. (Pilots in the current study were flying VFR, whereas pilots in [10] were flying IFR and were required to request approval for deviations from their filed route).

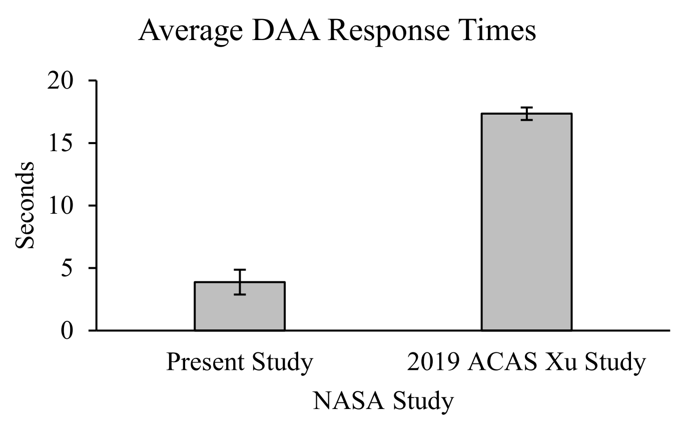


Fig. 10 Average DAA response times of current ACAS X_R study versus previous ACAS X_U study.

The Automated RA condition was designed to automatically comply with Horizontal and Vertical RAs according to the rates assumed by ACAS X_R, namely, standard rate turns for Horizontal RAs and +/- 1000fpm for Vertical RAs. While being trained to respond at those same assumed rates, however, pilots had the ability to respond more conservatively or more severely. Maneuver deviation sizes were nearly identical for Vertical RAs between the Auto and Manual RA conditions, indicating that pilots used approximately the same vertical rate used by the automation. For Horizontal RAs, though, pilots were found to use a faster turn rate than the automation, which led to heading changes that were 12° greater in the Manual RA condition and resolved the RA alerting 4 seconds sooner than in the Automated RA condition. While some pilots indicated a slight preference for turning faster than the standard rate due to the severity of a given conflict, this difference was likely also a function of the high sensitivity used by the inceptor and an inability for pilots to directly control the turn rate. Pilots were using the right inceptor to set the bank angle, which required an 18° bank angle at their airspeed to achieve the standard rate turn. Regardless of RA condition, pilots were forced to make large heading changes (83°-95°, on average) in order to fully comply with Horizontal RAs. The larger heading changes in the Manual RA condition were a result of pilots' faster turn rates leading to additional target heading updates, which extended the duration of the turn RAs.

When manually responding to DAA encounters in the current study, pilots were surprisingly balanced, evenly distributing the proportion (32-35%) of horizontal, vertical, and blended maneuvers. While not reported in the previous study [10], the authors did collect the proportion of maneuver types in a previous study with ACAS X_U. In that study, 63% of maneuvers were horizontal, 35% were vertical, and 2% were blended. The prevalence of horizontal maneuvers in a study with ACAS X_U is likely a result of pilots being situated at a ground control station and therefore experiencing the traffic information primarily through a top-down, two-dimensional context (see Fig. 11), which is weighted in favor of horizontal maneuvers. Conversely, pilots in the current study were in situ and were more likely to resolve maneuvers in the vertical dimension and in both dimensions simultaneously. While frequent blended maneuvers were noted, what was not captured was the size of the deviations in blended maneuvers. It is therefore possible that there was a primary dimension used in blended maneuvers, with pilots making a smaller, subsequent maneuver in the opposite dimension to gain a bit more separation from the intruder. As one would expect, pilots tended to make smaller deviations for DAA conflicts than RA conflicts, since they initiated those maneuvers earlier in the encounter progression.

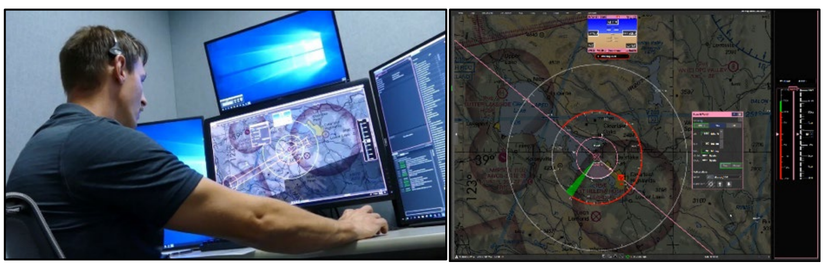


Fig. 11 Uncrewed, ground control station configuration for previous ACAS X_U study. Remote pilot situated in front of Tactical Situation Display with top-down view of aircraft and airspace.

Pilots successfully complied with the RAs issued by ACAS X_R more than 90% of the time. Compliance rates were consistent between the Manual and Automated RA conditions, suggesting pilots were no more likely to contradict RAs when they were responsible for implementing the maneuver. The leading factor for pilots failing to comply with Vertical RAs was proximity to terrain during a Descend RA. While future versions of ACAS X_R will leverage terrain and obstacle height information when issuing RAs, the alerting sensitivity that ACAS applies to that data set (e.g., the point at which Descend RAs are inhibited) is critical and must incorporate pilot feedback if instances of non-compliance are to be minimized. The primary factor for pilots failing to fully comply with Horizontal RAs revolved around pilots considering the horizontal maneuvers as excessive, requiring maneuvers that were too large, issuing too many target heading updates (38% of Horizontal RAs included at least two target heading updates), or commanding a horizontal maneuver when a vertical maneuver would much more effectively resolve the conflict. Despite the instances of RA non-compliance noted in the current study, the rates observed presently are consistent with those reported for ACAS X_U RA compliance in [10], which saw compliance rates of ~95% for Horizontal and Vertical RAs.

Overall, pilots rated the DAA and RA guidance provided by ACAS X_R as effective and easy to understand. This is noteworthy because it is the first time that the DAA, Horizontal, and Blended RA alerts and guidance were presented within a crewed aircraft configuration. Pilots considered the DAA guidance as potentially useful in VFR operations, suggesting that some operators of crewed vehicles may choose to enable the DAA functionality even if not required to do so for certification. Consistent with the causes of RA non-compliance, pilots reported that future versions of ACAS X_R would benefit from integration with terrain and obstacle databases (assuming it is tuned appropriately for eVTOL/AAM-type operations) and more frequent utilization of vertical advisories, especially when complying with a Horizontal RA will likely lead to a prolonged avoidance maneuver. When Horizontal RAs are issued, pilots would prefer it if they were updated less frequently and if the system minimized the required magnitude of the heading change.

Pilots rated the automated RA and RTC functions as effective, albeit with the Auto RA feature receiving higher ratings than Auto RTC. High ratings for automated RAs are not surprising, since their translation to maneuvers that the vehicle can execute are straightforward and the automation always performed perfectly in the present study. Slightly more surprising was the positive evaluation of the automated RTC function, which is a far trickier behavior to automate, since ACAS X_R does not explicitly indicate if or when a return to course is conflict-free. The simple logic employed in this study – i.e., wait for all DAA and RA banding to disappear from the display and add a 5-second buffer – managed to largely avoid cases of re-engaging traffic conflicts and thereby avoided the need for pilots to disengage the automated RTC maneuver. Pilots were found to disengage the auto-RTC function in 12% of cases, compared to 7% disengagement of the auto-RA function. Despite the high ratings for the Auto RA condition, only a slight majority (58% to 42%) preferred it to the Manual RA condition.

Finally, pilot self-ratings of workload indicated low levels across all NASA TLX sub-scales and across all conditions. Pilot ratings also indicated that they received sufficient training and were provided with the necessary displays and interfaces to test the objectives of this study.

Taken together, the results of this paper suggest that ACAS X_R alerting and guidance, including DAA elements that were originally designed for remote pilot configurations, may be transferable to a crewed eVTOL configuration. Despite the general positive findings reported here, there are numerous areas requiring improvement and further research. In particular, how terrain and obstacle information is incorporated and tuned for eVTOL/rotorcraft operations and subsequently presented to pilots is going to be crucial for achieving future pilot acceptance. Additionally, whether or not the ACAS X_R logic is appropriate in all flight regimes (including low-speed regimes unique to rotorcraft) remains to be tested in a HITL environment and cannot be inferred from the present findings since the current study was limited to en route scenarios. Examining the use of DAA in more complex AAM scenarios – such as in higher traffic densities and with new airspace configurations (e.g., corridors) – is also necessary to more thoroughly assess the acceptability of DAA to AAM operations. Lastly, the use and presentation of horizontal RAs was repeatedly mentioned as a weakness of ACAS X_R and deserves continued study. Limitations of the current study that future studies can hopefully address include, but are not limited to: lack of background traffic and other airspace users (e.g., ATC), the use of perfect (i.e., non-noisy) surveillance and ownship data, a lack of simulated winds, and the inability to see traffic with the simulator's out-the-window visualization.

Acknowledgments

The authors wish to thank NASA's Airspace Operations and Safety Program's Advanced Air Mobility project for funding this work. Additionally, the authors thank Thomas Quinonez and Jonathan Luk of ASRC Federal Data Solutions, LLC for the hardware and software development and support on the simulator used during the study.

References

[1] Johnson, W., Silva, C., and Solis, R., "Concept Vehicles for VTOL Air Taxi Operations," *AHS Technical Conference on Aeromechanics Design for Transformative Vertical Flight*, San Francisco, CA, January 2018.

[2] Federal Aviation Administration, "*Urban Air Mobility, Concept of Operations, v2.0*," *FAA* [online database], URL: https://www.faa.gov/sites/faa.gov/files/Urban%20Air%20Mobility%20%28UAM%29%20Concept%20of%20Operations%202.0_0.pdf [retrieved 1 May 2023].

[3] Federal Aviation Administration, "*Pilots' Role in Collision Avoidance*," Report AC 90-48D, 2016.

[4] Conway, E. M., *Blind landings: Low Visibility Operations in American Aviation, 1918–1958*, Johns Hopkins University Press, Baltimore, 2006.

[5] Hobbs, A., *Limitation of the See-And-Avoid Principle*, Australian Transport Safety Bureau: Transport Safety Report, Canberra, Australia, 1991, URL: https://skybrary.aero/sites/default/files/bookshelf/259.pdf [retrieved 4 January 2023].

[6] National Air Traffic Controllers Association, "A History of Air Traffic Control," *NATCA* [online database], URL: https://www.natca.org/wp-content/uploads/2019/12/NATCA_ATC_History.pdf [retrieved 4 January 2023].

[7] Brooker, P., "Reducing Mid-Air Collision Risk in Controlled Airspace: Lessons from Hazardous Incidents. *Safety Science*, Vol. 43, No. 99, 2005, pp. 715–738.

[8] Kochenderfer, M. J., Holland, J. E. and Chryssanthacopoulos, J. P., "Next-Generation Airborne Collision Avoidance System," *Lincoln Laboratory Journal* [online journal], Vol. *19*, No. 1, pp. 17–33, URL: https://www.ll.mit.edu/sites/default/files/page/doc/2018-05/19_1_1_Kochenderfer.pdf [retrieved 4 January 2023].

[9] Lincoln Laboratory, "Airborne Collision Avoidance System X," Massachusetts Institute of Technology: *Tech Notes* [online database]. URL: https://apps.dtic.mil/sti/pdfs/ADA625750.pdf [retrieved 4 January 2023].

[10] Rorie, R. C., Smith, C. L., Sadler, G. G., Monk, K. J., Tyson, T. L., and Keeler, J. N., "A Human-in-the-Loop Evaluation of ACAS X_U," *AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*, San Antonio, TX, 2020, pp. 1-10.

doi: 10.1109/DASC50938.2020.9256618
[11] Smith, C. L., Rorie, R. C., Monk, K. J., Keeler, J., and Sadler, G. G., "UAS Pilot Assessments of Display and Alerting for the Airborne Collision Avoidance System X_U," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, Vol. 64, No. 1, 2020, pp. 159–163.
doi: 10.1177/1071181320641040
[12] RTCA, "Minimum Operational Performance Standards (MOPS) for Detect and Avoid (DAA) Systems Revision B," No. DO-365B, RTCA, Washington, DC, 2020.
[13] Sadler, G. G., Rorie, R. C., Smith, C. L., Keeler, J., and Monk, K. J., "Display and Automation Considerations for the Airborne Collision Avoidance System Xu." *AIAA AVIATION 2020 FORUM* 2020, 2020-2854, AIAA, Virtual Event, 2020.
doi: 10.2514/6.2020-2854
[14] Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., "VTOL Urban Air Mobility Concept Vehicles for Technology Development," *2018 Aviation Technology, Integration, and Operations Conference*, AIAA, 2018.
doi:10.2514/6.2018-3847.
[15] Archdeacon J. L., Iwai N. H., and Feary, M., "Aerospace Cognitive Engineering Laboratory (ACELAB) Simulator for Electric Vertical Takeoff and Landing (eVTOL) Research and Development," *AIAA AVIATION 2020 Forum*, 2020-3187, AIAA, Virtual Event, 2020.
doi: 10.2514/6.2020-3187
[16] Lombaerts, T., Kaneshige, J., Schuet, S., Hardy, G., Aponso, B., and Shish, K., "Dynamic Inversion Based Full Envelope Flight Control for an eVTOL Vehicle using a Unified Framework," *Proceedings of the AIAA Scitech 2020 Forum*, Orlando, FL, 2020, p. 1619.
doi: 10.2514/6.2020-1619
[17] Hart, S. G., "NASA-Task Load Index (NASA-TLX), 20 years later," *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, Vol. 50, No. 9, HFES, Santa Monica, CA, 2006, 904–908.