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United States Army Aeromedical Research Laboratory

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Pilot Cueing for 360° Obstacle Awareness During DVE Missions

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14. ABSTRACT
A study was conducted to evaluate the effectiveness of a trimodal display suite designed to aid pilots in detecting and avoiding obstacles during flight in degraded visual environment (DVE) conditions. The display suite integrated visual, spatial-auditory, and tactile display elements which consist of the Integrated Cueing Environment-Collision Avoidance Symbology (ICE-CAS) blended with the Primary Flight Display (PFD) symbology, the Integrated Collision Avoidance Display (ICAD) overlaying a panel-mounted display (PMD), the Augmented-Reality Spatial Auditory Display(ARSAD), and the Tactile Situational Awareness System (TSAS). The visual ICE-CAS symbology was displayed on either a helmet mounted display (HMD) or PMD. Ten total pilots participated in the study to evaluate the effectiveness of the cueing types while performing several operational flight tasks in a UH-60 Black Hawk simulator. To assess the effectiveness of the cueing types, objective measures including flight performance metrics and pilot biometric responses, as well as subjective measures including pilot ratings for workload, situational awareness, and system usability were collected. Eye tracking and pupillometry data were also collected as additional workload and usability measures. Results from the study suggest additional cueing leads to favorable performance increases and reduced workload, but no firm conclusions could be made.

15. SUBJECT TERMS
Degraded Visual Environment (DVE); Integrated Cueing Environment (ICE); pilot cueing; multimodal cueing

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Summary

A study was conducted to evaluate the effectiveness of a trimodal display suite designed to aid pilots in detecting and avoiding obstacles during flight in degraded visual environment (DVE) conditions. The display suite integrated visual, spatial-auditory, and tactile display elements that consisted of the Integrated Cueing Environment-Collision Avoidance Symbology (ICE-CAS) blended with the Primary Flight Display (PFD) symbology, the Integrated Collision Avoidance Display (ICAD) overlaying a panel-mounted terrain display (PMD), the Augmented-Reality Spatial Auditory Display (ARSAD), and the Tactile Situational Awareness System (TSAS). The visual ICE-CAS symbology was displayed on either a helmet mounted display (HMD) or panel mounted display (PMD). Ten total pilots participated in the study to evaluate the effectiveness of the cueing types while performing several operational flight tasks in a UH-60 Blackhawk simulator. Objective and subjective measures were collected to assess the effectiveness of cueing types. Objective measures included flight performance metrics and pilot biometric responses. Subjective measures included pilot ratings for workload, situational awareness (SA), and system usability. Eye tracking and pupillometry data were also collected as additional workload and usability measures. Results from the study suggest additional cueing leads to favorable performance increases and reduced workload, but no firm conclusions could be made.

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Table of Contents

List of Figures

List of Tables

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Introduction

In 2018, the US Army released a solicitation for a next generation of Future Vertical Lift (FVL) Attack Reconnaissance Aircraft (FARA) to fly in 2022 and begin fielding in 2028.

The FARA solicitation states: Army Aviation must operate in highly contested/complex airspace and degraded environments … The Army currently lacks the ability to conduct armed reconnaissance, light attack, and security with improved stand-off and lethal and non-lethal capabilities with a platform sized to hide in radar clutter and for the urban canyons of megacities.

Operations in megacities will require many of the same aviation capabilities of attack, reconnaissance, assault, and medical evacuation currently used in operations in less dense terrain, but with considerable constraints. For example, megacities offer limited landing and pickup zones. Flying close enough to Soldiers on the ground to provide air support introduces the obstacles of powerlines, antennas and satellite dishes, and narrow flight patterns between buildings.

Operations in the Iraq and Afghanistan theaters have determined that flying in degraded visual environments (DVE) pose a significant risk to helicopter operations. DVE can result from partial or total loss of visibility from airborne dust, sand, or snow obscuration caused by the helicopter's rotor downwash (known as brownout or whiteout). Clouds, haze, fog, and starless nights can also cause DVE. These conditions significantly modify the pilot's capability to use the natural out-of-the-window (OTW) perceptual cues, increase workload and lead to failure to maintain sufficient clearance with the obstacle, resulting in an increased likelihood of collision with terrain (CFIT), natural objects (e.g., trees) or erected structures (e.g., buildings, poles, towers and wires). According to a recent US Army Aviation accident report (Feltman et al., 2018) from Fiscal Year 2011 through Fiscal Year 2015, 31% of events for Class A and 17% of the events for Class B were classified as collision related. Among obstacles, wires represent a specific hazard due to their near invisibility. During the 1994-2003 period, US Army helicopters were involved in 1,160 accidents, in which 34 were wire strikes that resulted in seven fatalities (Nagaraj & Chopra, 2008).

Current sensors provide imagery, which is fused with, or overlaid on, enhanced synthetic vision (ESV) three-dimensional (3D) terrain and/or electro-optical/infrared (EO/IR) imagery. The presentation of realistic, fused terrain/obstacle imagery "augments" the natural scene perception through helmet-mounted display (HMD) or windscreen projected "head-up" display (HUD). Combined with abstract, non-conformal two-dimensional (2D) or conformal 3D symbology (3D CS) superimposed on a multi-function display (MFD) or HUD (Head Up Display), the sensory imagery supports guidance and control especially during operations in DVE. Although EVS and synthetic vision systems (SVS) can improve pilot's situation awareness (SA) by lowering workload, they can also mislead and produce clutter and attentional tunneling (Wickens & Alexander, 2009). Given this, they might not provide the maximally effective depiction of the environment around the helicopter. Indeed, visual displays provide only a partial representation of the threat space due to their limited field-of-view (FOV) or the 2D exocentric representation of space.

Thus, use of alternate sensory modalities that can support a natural, ecologically saalient, egocentric 360° representation of the environment around the aircraft may provide improved SA and reduced pilot workload. Augmented-reality spatial-auditory displays are natural candidates for the task. These displays enable the creation of a virtual auditory space where auditory objects behave realistically in terms of direction, distance, and motion. Tactile displays are another option that can also support a partial representation of the 3D space, albeit with a lower resolution and typically limited to cueing direction and motion. Spatial-auditory cueing can be an effective terrain/obstacle avoidance display alone or in combination with visual or tactile cues. An optimized method for displaying the environment to the helicopter aircrew while maintaining an acceptable workload remains unknown.

The current work presented within this report is part of a continued research effort aimed at identifying the ideal modality or combination of modalities to present informational cues to pilots during DVE flight. Ongoing efforts within the DVE Mitigation program (DVE-M) have resulted in a series of studies examining the use and display of tactile, auditory, and visual cues for flight in DVE (Russell et al., 2016; McAtee et al., 2017; Feltman et al., 2018). The results of these studies have led to further development and refinement of a multimodal cueing package known as the Integrated Cueing Environment (ICE). Moreover, the current work is an extension of an earlier version of visual-auditory display for obstacle avoidance research presented by Miller (2018, 2019) and Godfroy-Cooper (2018, 2019). The current work adds a tactile component and a parametric Threat Space model for defining the Caution and Warning cueing regions.

To-date, the studies examining cueing under the DVE-M program have focused mainly on the utility of ICE during takeoff, flying en-route and approach-to-landing in DVE. This study built upon previous studies by assessing different cueing modalities where obstacles are present on the flight path. Specifically, the study assessed visual symbology, tactile and spatial-audio cueing designed to help pilots detect and avoid obstacles during flight in an urban area of operation.

Methods

This study was reviewed and locally approved by the U.S. Army Aeromedical Research Laboratory's Research Compliance Office. Institutional Review Board approval was not sought for this study, as it was determined non-research. As such, the information reported here is only specific to the cueing systems that were assessed in this particular study, and are not generalizable.

Study Design

Ten pilots flew ten mission scenarios designed to assess the multimodal cueing for obstacle avoidance. Pilots also flew two additional scenarios to assess clearance line symbology, although these data are not reported here. Flight performance metrics, subjective measures and biometric data were collected during the ten scenarios.

Participants

Ten male pilots participated in this study. Eight of the pilots were UH-60 pilots, one pilot was an HH-60 Pave Hawk pilot, and one an AH-64 pilot. The UH-60 pilots were recruited to evaluate the effectiveness of the cueing from the perspective of operational UH-60 pilots who have limited experience with advanced cueing symbology, whereas the HH-60 Pave Hawk and AH-64 pilots were recruited to evaluate the effectiveness of cueing from the perspective of those with experience in using advanced cueing symbology. Performance and biometric data from the UH-60 pilots were analyzed and are reported separately from that of the two additional pilots.

UH-60 Demographics.

The eight pilots were Active Duty Army pilots (n = 8) with years of military service ranging from 8 to 21 (M = 13.88 years, SD = 4.61 years). The pilots included one commissioned officer (Captain) and five warrant officers including three with the rank W3 and two pilots with the rank of W2. UH-60 flight hours ranged from 470 to 2,060 (M = 1,390, SD = 476.06), while total flight hours ranged from 540 to 2,060 (M = 1478.75, SD = 440.37).

Procedure

Pilots participated in the study over a period of two consecutive days. The first day included a safety and risk briefing, description of the study's purpose and instrumentation, completion of demographics, sleep and psychophysiological questionnaires (for data interpretation purposes only and not reported in results), classroom training, and simulator flight training.

At the end of the simulator training, the research pilot determined whether the evaluation pilot was proficient with the cueing sets in order to proceed with testing. Once proficiency was established, a brief lunch break occurred. After the break, the evaluation pilot was fitted with the biometric recording devices and baseline biometric data were recorded (see Appendix B for details). Next, the pilots completed five simulation trials with either the PMD or HMD using the randomized cueing combinations. The cueing conditions and display type (PMD or HMD) are shown in Table 1.

On the second day, each pilot was offered additional training. Following this, the pilot was fitted with biometric recording devices and baseline biometric data were collected. Next, the pilot completed the final five simulation trials with either PMD or HMD. At the end of each of the flight trials, pilots completed the subjective measures. Additional demonstration flights were completed, but are not reported here. At the end of the second day, the final subjective measures were completed and the pilots participated in an AAR.

Data for pairs of conditions were combined to form five configurations for analyses, described in Table 2 below.

Table 1. Study conditions.

Condition #	Cueing	Modality	Display
1	ICE	Baseline	PMD
2	ICE-CAS	Visual	PMD
3	ICE-CAS +ARSAD	Visual + Auditory	PMD
4	ICE-CAS +TSAS	Visual +Tactile	PMD
5	ICE-CAS +ARSAD+TSAS	Visual + Auditory+ Tactile	PMD
6	ICE	Baseline	HMD
7	ICE-CAS	Visual	HMD
8	ICE-CAS +ARSAD	Visual + Auditory	HMD
9	ICE-CAS +TSAS	Visual +Tactile	HMD
10	ICE-CAS ARSAD+TSAS	Visual + Auditory+ Tactile	HMD

Table 2. Configuration Descriptions

Cueing Configuration	Conditions	Abbreviation
Baseline	1 and 6	BL
Visual Only	2 and 7	V
Visual + Audio	3 and 8	VA
Visual + Tactile	4 and 9	VT
Visual + Audio + Tactile	5 and 10	VAT

Statistical Approach and Quality Control

Mixed effects linear regression models were used to evaluate the effects of cueing on each of the dependent flight metrics. Cueing configuration variables were considered fixed effects and subject was a random effect. In some cases, transformation of the response variable was required to meet model assumptions. Examination of flight metrics reported in the main body of the paper include the effects of the cueing modality configurations on the metrics described in Table 2 above. Subjective data were examined using Wilcoxon signed rank tests. Flight data were first examined for outliers. Outliers were identified as greater than two standard deviations (SDs) away from the mean, and missing values were excluded using listwise deletion.

Of note, the results of this study are likely underpowered due to the low number of participants, and as such, results should be interpreted with caution. Additionally, the pilots who participated in this study had a wide range of flight experience, which increased variability in the data and further reduced power. Moreover, the data collected and presented here are not generalizable beyond the scope of this study.

Materials

Flight Simulator

All flights were conducted in the U.S. Army Aeromedical Research Laboratory's (USAARL) NUH-60FS Blackhawk simulator. The NUH-60FS is fully accredited by the Directorate of Simulations (DoS) and by the Program Executive Office Simulations, Training, and Instrumentation (PEOSTRI), as a 6-Degree of Freedom (DOF), full-motion, and full-visual (Level D equivalent) NUH-60FS Black Hawk helicopter flight simulator. It has a Dell XIG visual image generator which can simulate natural helicopter environment surroundings for: day, dusk, night, dust, snow, rain, clouds, Night-Vision-Goggle (NVG), and Infrared (IR) characteristics. The simulator captures flight performance and simulator state characteristics at a rate of 60 Hz.

Symbology Sets and Cueing

A trimodal obstacle avoidance display was developed, integrating visual, spatial-auditory, and tactile display elements into the ICE (Godfroy-Cooper et al., 2019) to provide 360° SA around the aircraft. Two visual displays were designed. The first, displayed on the inboard PMD, provided a top-down terrain RADAR with obstacles color-coded and is termed the Integrated Collision Avoidance Display (ICAD). The second display was provided on the outboard PMD and integrated ICE visual symbology with Collision Avoidance Symbology (ICE-CAS) (Szoboszlay, Davis, Fujizawa, Minor, Osmon, & Morford, 2017). For the HMD condition, the ICE-CAS was presented on a SA Photonics Helmet Mounted Display (HMD). During the HMD test conditions, the ICAD was always available on the inboard PMD.

The Augmented-Reality Spatial-Auditory Display (ARSAD) (Miller, Godfroy-Cooper, & Wenzel, 2018; Godfroy-Cooper, Miller, Bachelder, & Wenzel, 2018; Miller, Godfroy-Cooper, & Szoboszlay, 2019) was developed to present the locations of the two most-urgent obstacles and the nearest power line segment using augmented-reality spatial sonifications. Ultimately, the locations of obstacles in the environment are provided by a multi-elevation 360° bumper RADAR system. For development, a simulator software Sensor Model was used to emulate RADAR behavior. Additionally, known locations of power lines were integrated into the model from a terrain database and were displayed by the ICAD and ARSAD.

To complement ARSAD, the Tactile Situation Awareness System (TSAS) was integrated to provide obstacle azimuth cueing using a 12-tactor belt, as well as warn of altitude conditions using a shoulder harness and seat cushion. Together, these four displays (ICAD, ICE-CAS, ARSAD, and TSAS) provide an integrated and unified trimodal display to warn of potential collisions in the vicinity of the aircraft, inside and outside the field of view. The augmented and multimodal displays provided an increased sense of immersion, SA, and spatial accuracy. Additionally, these displays provided redundancy in case of system failure, unimodal perceptual masking, or channel unavailability. This integrated display system has been experimentally evaluated in the NASA Ames System Integration Laboratory (SIL) simulator (Godfroy-Cooper, Miller, Bachelder, & Wenzel, 2018) and twice in USAARL's NUH-60FS Black Hawk helicopter flight simulator (Miller, Godfroy-Cooper, & Wenzel, 2018; Miller, Godfroy-Cooper, & Szoboszlay, 2019, and current work).

Obstacle Threat Assessment.

The radar sensor model.

To determine the location of obstacles in the environment, four Echodyne MESA-DAA RADARs with a beam width of 4° and beam height of 12° were installed on a UH-60 helicopter for inflight demonstration. This allowed three elevations to be scanned 360° in azimuth, with a 4° azimuth increment, at a 1.6 Hz update rate. The RADARs collectively swept 360° in azimuth at multiple elevations. Three elevation profiles were investigated, ascending, level, and descending flight, e.g., ascending covering -6° to 30° elevation, level -18° to +18°, and descending -30° to +6°. The pointing directions of the RADARs were modified based on ownship pitch and roll to approximate gimballed behavior.

Given that the display elements are being prototyped and evaluated in helicopter simulators before migrating to the physical platform, the RADAR behavior is approximated by a Sensor Model. Since the ascending and descending algorithms have yet to be completed, the level flight elevation range was assumed with gimballed behavior. Professional simulators often provide the capability of doing hit testing using a virtual laser polygon hit test. This allows the virtual environment to be scanned in a fashion analogous to RADAR sweeps in the real world (albeit more like the tight beam of a laser, rather than the broad beam of RADAR). The azimuth increment is every 0.75° with an update rate of 2 Hz for a full scan. The location and height of Power Line Towers were available from a database. A power line represented a special case of an obstacle in that it was a database object versus a RADAR sensed object (though it can be sensed as well). The Power Line symbology consisted of a conformal dashed line superimposed over powerlines and towers when within 1 kilometer (3281 ft) of ownship. The line color indicates the clearance state, orange below and blue cleared. The helicopter was considered clear of the power line once the landing gear exceeded 30 ft above the line.

The Threat Space.

A static-obstacle Threat Assessment (Miller, Godfroy-Cooper, & Szoboszlay, 2019) maps static obstacle threats in the vicinity of the helicopter to a normalized threat value that can be ordered and sorted to determine the obstacles of greatest urgency (Figure 1). The Threat Assessment uses a threat scale from 0 to 1 where 0 corresponds to the periphery of a 3D Threat Space and 1 corresponds to the helicopter blade radius sphere. The shape of the Threat Space is fixed and spherical at low speeds (less than 7.3 knots) and extends in the direction of the velocity vector as speed increases.

The Threat Space is composed of two regions, an outer Caution region and an inner Warning region. The Threat Space parameters that follow were selected based on region preference data from 15 U.S. Army helicopter pilots. The Caution region was considered the region where obstacle SA is required. The Warning region was defined as the region where an evasive maneuver is needed. The max extent of the Caution region is defined by a time-to-collision (TTC) value of 6.5 knots, the max extent of the Warning region by a TTC of 3.0 knots. At 7.3 knots, the Threat Space begins to ignore threats from the rear. All sensor hits are mapped into this space to determine their threat level. The threat values are then sorted to determine the most urgent (aka Urgent 1) and second-most urgent (aka Urgent 2) sensor-detected obstacles for presentation.

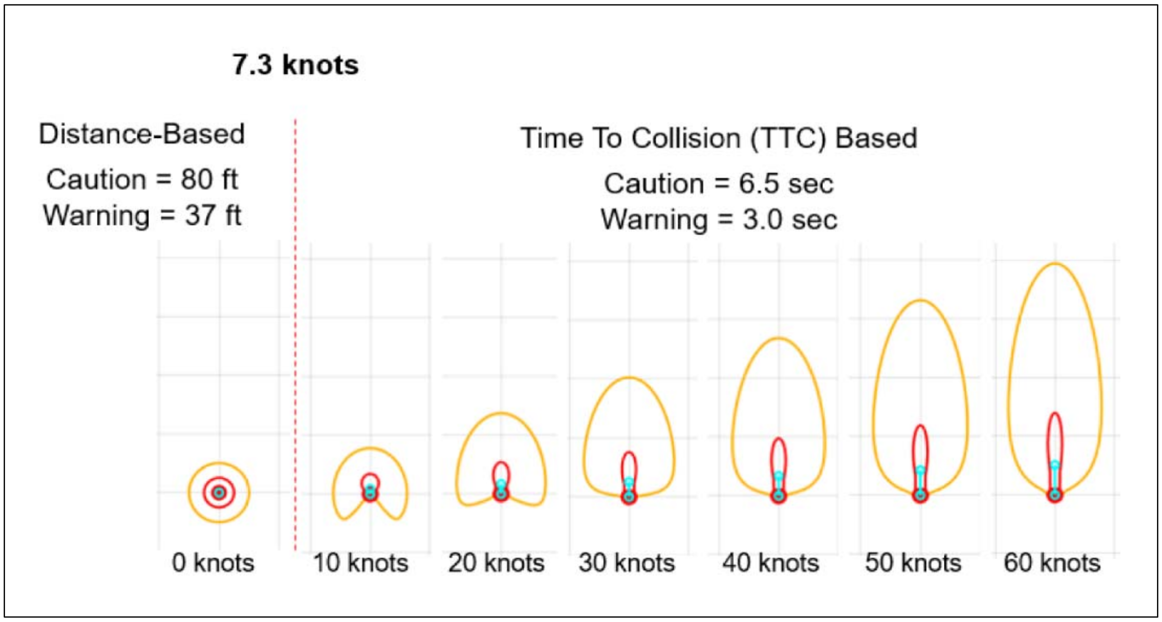


Figure 1. The speed-dependent evolution of static obstacle Threat Space for two cueing regions, Caution and Warning (corresponding to the static Threat Tune defaults). The Threat Space is Distance-Based below 7.3 knots, and Time-To-Collision Based above 7.3 knots. At 7.3 knots, the Threat Space begins to ignore threats from the rear. 2D slices through 3D threat volumes are shown on planes containing the velocity vector (cyan line).

Threat Level.

A categorization of the Threat Space was performed to assess the Time on Task spent within a Caution region, a Warning region, and a Rotor Disc region, where the obstacle is within a 27ft blade radius sphere (likely a Controlled Flight Into Terrain, but not necessarily). Regarding the Threat Level parameter, the Warning region threshold is defined by:

(1) threatWarning = 1 – ttcThreshWarningsS/ttcThreshCautionS

The Warning Threat Level Threshold was set at: 1 - 3.0/6.5 = 0.5385 (0: obstacle outside of Caution and Warning Threat Space; >0 to <0.5385: obstacle in Caution region; 0.5386 to <1.0: obstacle in Warning region, 1.0: obstacle within 27 ft blade radius sphere).

Ground and down rejection.

Given the -18° sensor scan (and potential lower elevation scans), several ground hits can occur, especially during takeoff, landing, and taxiing (Figure 2). Since in these conditions the pilot is typically more aware of the ground than other potential obstacles in the environment, a ground filter was introduced. The ground filter rejects sensor hits below 10 ft above the ground. This also helps to avoid oversaturation and to reduce the annoyance and distraction of the alerts. Similarly, if the pilot is flying Nap-of-the-Earth, the pilot is intentionally flying near objects beneath the helicopter, necessitating a down filter. The down filter rejects sensor hits 30 ft below the helicopter's landing gear. When used together, one seamlessly transitions into the other as shown in Figure 2.

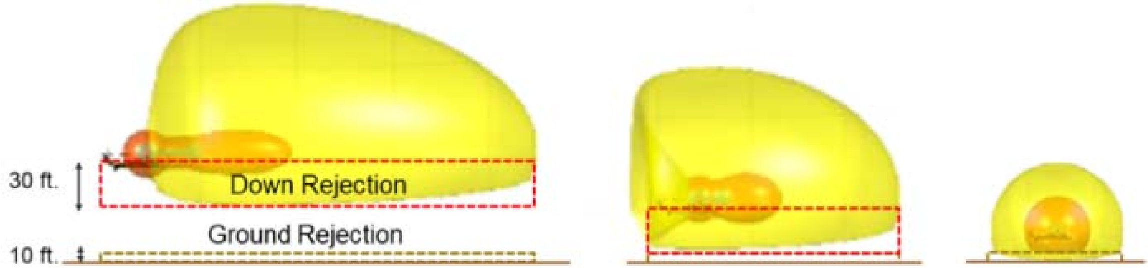


Figure 2. Down Rejection transitioning to Ground Rejection for a Down Rejection Offset of 30 ft and a Ground Rejection Height of 10 ft.

Angular rejection and the two most urgent obstacles.

A goal of the display design was to warn of two sensed obstacles simultaneously. Thus, all sensor hits were mapped via the Threat Assessment to threat values and sorted. The hit with the highest threat level was then assigned to be Urgent 1. Given a sensor azimuthal angular scan pattern and resolutions on the order of a few degrees, it was necessary to avoid warning of two adjacent hits on the same obstacle. Also, Urgent 1 will have already cued that general region of space as a threat. This yielded an Angular Rejection of 45°, a +/- azimuth angle about Urgent 1 specifying a region to omit from the search for Urgent 2 (Figure 3). In the previous design iteration (Miller, Godfroy-Cooper, & Wenzel, 2018; Godfroy-Cooper, Miller, Bachelder, & Wenzel, 2018), Angular Rejection was termed "tolerance" and set to 90°. For the present iteration, the evaluation is taking place in a dense urban environment where a higher resolution might prove useful.

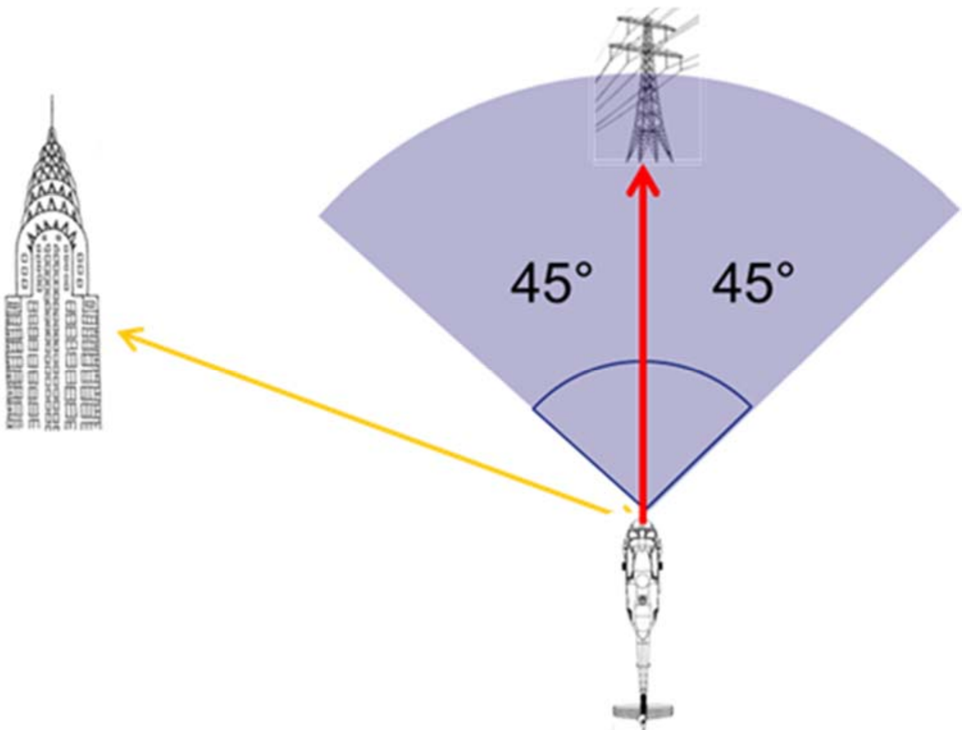


Figure 3. The sensor Angular Rejection window of ±45° about Urgent1 to omit from the search for Urgent2.

Once the two most-urgent obstacles (Urgent 1, Urgent 2) were identified via the Threat Assessment described above, they were presented to the pilot using the trimodal layered visual-auditory-tactile display approach (see later section for details). In addition to sensor-detected obstacles, the display also included one database obstacle type, power lines. In past experiment debrief sessions (Miller, Godfroy-Cooper, & Szoboszlay, 2019), pilots commented that power lines (or wires, in general) would be the primary instance in which the obstacle type would be important. Thus, due to their unique and significant threat, power line tower locations were stored in a database and presented with power-line specific visual symbology and sonifications. In the future system, when detected by the sensor, a power line hit will also be treated as a general sensor-detected obstacle.

ICE-Collision Avoidance Symbology (Primary Flight Display outboard PMD).

The ICE visual symbology (Figure 4) was used as the baseline visual symbology set during the evaluation. ICE utilizes a 3D Conformal landing zone which refers to a three-dimensional (3D) perspective view of the landing point when added to the base two-dimensional (2D) ICE symbology set. This symbology system is a tailored set of rotorcraft symbology with guidance to allow for safe landings in DVE.

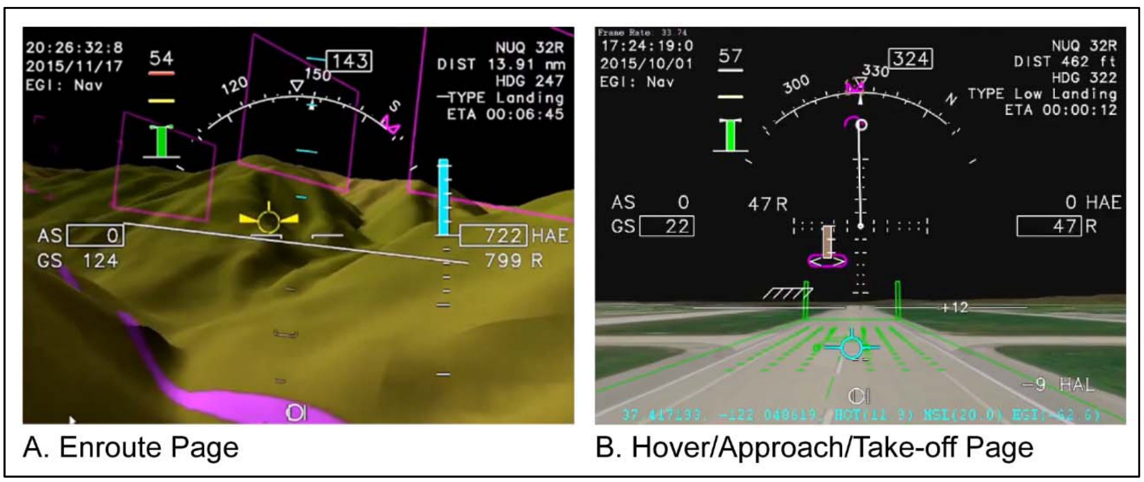


Figure 4. Baseline ICE Symbology. Baseline ICE Symbology. Left: Enroute page. Right: Hover/Approach/Take-off Page.

The PMD 360 SA display presented baseline ICE and ICE-CAS elements (Figure 5) and scene-linked conformal symbology superimposed over a FLIR image (FOV 60° x 45°). The ICE “Highway in the Sky” indicating the direction of flight was flattened and presented as magenta chevrons overlaying the terrain. This modification was chosen in order to better test the trimodal obstacle avoidance cueing, although a previous study (Feltman et al., 2018) demonstrated the “Highway in the Sky” to improve performance and reduce workload, as compared to the chevrons.

When in the field of view, the two most-urgent obstacles were rendered on the PMD using diamonds colored according to their Threat Assessment threat level. A threat of near 0 (Caution threshold) colored yellow linearly transitions to a threat of 1.0 (blades) colored red. They were presented as fixed-sized billboards so that their size increases as the obstacle nears providing a visual looming effect. Their dimensions were 30' x 30' so that their visual extent approximately matched the RADAR beam width of 4° at 200 ft.

Figure 5. The outboard PMD displayed the Integrated Cueing Environment-Collision Avoidance Symbology (ICE-CAS) overlaid on the Forward Looking InfraRed (FLIR) image. In this Figure, the yellow diamond indicates the most urgent obstacle. The Diamond's color indicates the threat level from 0 (yellow) to 1 (red). A conformal line is superimposed over powerline wires and towers with the color indicating clearance, orange below, blue cleared.

Integrated Collision Avoidance CAD (ICAD) Multifunction Display (inboard PMD).

The Integrated Collision Avoidance Display (ICAD) is a Helicopter Terrain Awareness and Warning System (HTAWS) that includes sensor-detected obstacle information and power line symbology. It presents the terrain, power line, and RADAR information in an exocentric 2D top-down heading-up moving map and the Threat Assessment and obstacle information with a 2.5D axis (Figure 6). This configuration facilitates an intuitive mapping with the OTW, ICE-CAS/PFD, ARSAD, and TSAS egocentric reference frames (ERFs). The map viewpoint zoomed in 6 knots and below to provide additional detail for low-speed maneuvers.

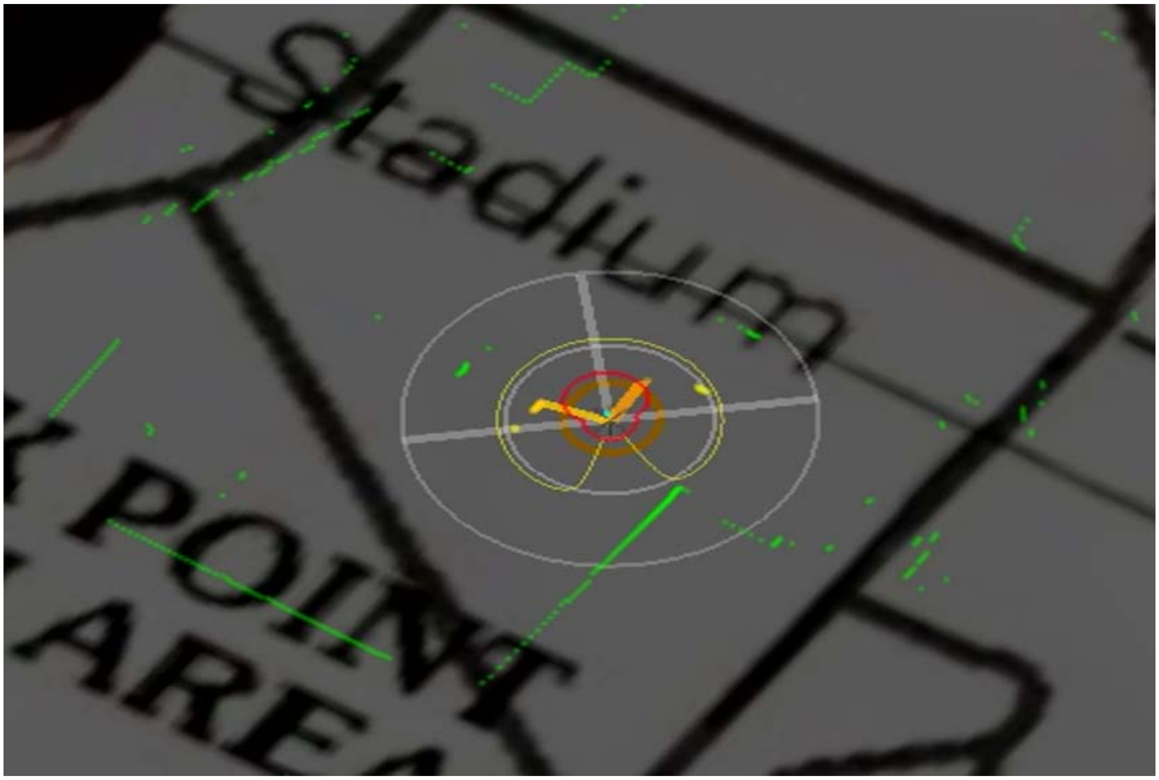


Figure 6. The Integrated Collision Avoidance Display is a Helicopter Terrain Awareness and Warning System (HTAWS) that includes sensor-detected obstacle information and power line symbology. It presents the terrain, power line, and RADAR information in an exocentric 2D top-down heading-up moving map and the Threat Assessment and obstacle information with a 2.5D axis (Figure 6). This configuration facilitates an intuitive mapping with the OTW, ICE-CAS/PFD, ARSAD, and TSAS egocentric reference frames (ERFs). The map viewpoint zooms in 6 knots and below to provide additional detail for low-speed maneuvers.

The 2.5D display included a terrain map superimposed with a magenta ground track line, power line symbology, and RADAR hits color-coded to their threat level (see the color mappings in Figure 6). Two vectors were drawn from the ownship to the two most urgent obstacles which are also color coded to their threat level. The RADAR hits, obstacle vectors, and diamonds were all shown using the same yellow Caution threat 0.0 to red Warning threat 1.0 color scale. The heading-relative ICAD vector, ICE-CAS diamond (when within the FOV), ARSAD spatial sonification, and tactor stimulus (Urgent 1 only) all point the same direction, reinforcing the rapid acquisition of obstacle incidence angle.

The 2D presentation of a 3D threat space.

With this iteration of the obstacle avoidance display, the sensor obstacle hits, and the corresponding Threat Assessment expanded to include regions off the horizontal plane. This resulted in the Threat Space volume shown in Figure 6 that always pointed in the direction of the velocity vector. Previously, the Caution and Warning regions were superimposed on the terrain map (and RADAR hits) to provide a safety profile of threat in the vicinity of ownship. To preserve this concept, the new safety profile took advantage of the radial symmetry of Threat

Space to rotate and tilt a horizontal plane into alignment with the velocity vector along the plane's longitudinal axis.

A circular rule and the Threat Space Caution and Warning contours can then be drawn on this tilted plane to create a 2.5D safety profile display using perspective rendering (Marr, 1982). The ownship-relative 2.5D circular rule included 100-ft and 200-ft radii circles for distance judgements, a 200-ft longitudinal axis in the direction of the velocity vector, and a 400-ft lateral axis. The rotation of the lateral axis depicted the azimuth of Threat Space while the 2.5D perspective effects provided elevation. Note, the lateral axis always remained a fixed display distance on an Earth-parallel horizontal plane and provided the axis about which the 2.5D display pivots. Figure 7 depicts a series of 2.5D displays where the azimuth of the velocity vector matches the heading and the elevation of the velocity vector was lowered from +80° to -80°. The contour lines correspond to a speed of 15 knots and the cyan line depicts the velocity vector.

Figure 7. The 2.5D depiction of a 15-knot 3D Threat Space between +80° (left) and -80° (right) velocity vector elevation relative to the horizontal plane. The rotation about the lateral axis provides the 2.5D effect.

Power line.

Being based on terrain database information, the ICAD Power Line segment symbology was attached to the moving map using linear orange segments between the towers. The nearest segment was highlighted with bands on either side that served as an altitude-to-go clearance indicator. When the helicopter landing gear were below the clearance altitude of 30 ft above the wire, this band flashed red at 1.5 Hz (Figure 8). When clear, this region was green and fixed. Note, in this iteration of testing, the clearance behavior was not matched auditorily other than by the perception of elevation cues. However, 1.5 Hz was selected as the flash rate to match the rhythmic behavior of the Power Line sonification to reinforce the multimodal depiction of the obstacle.

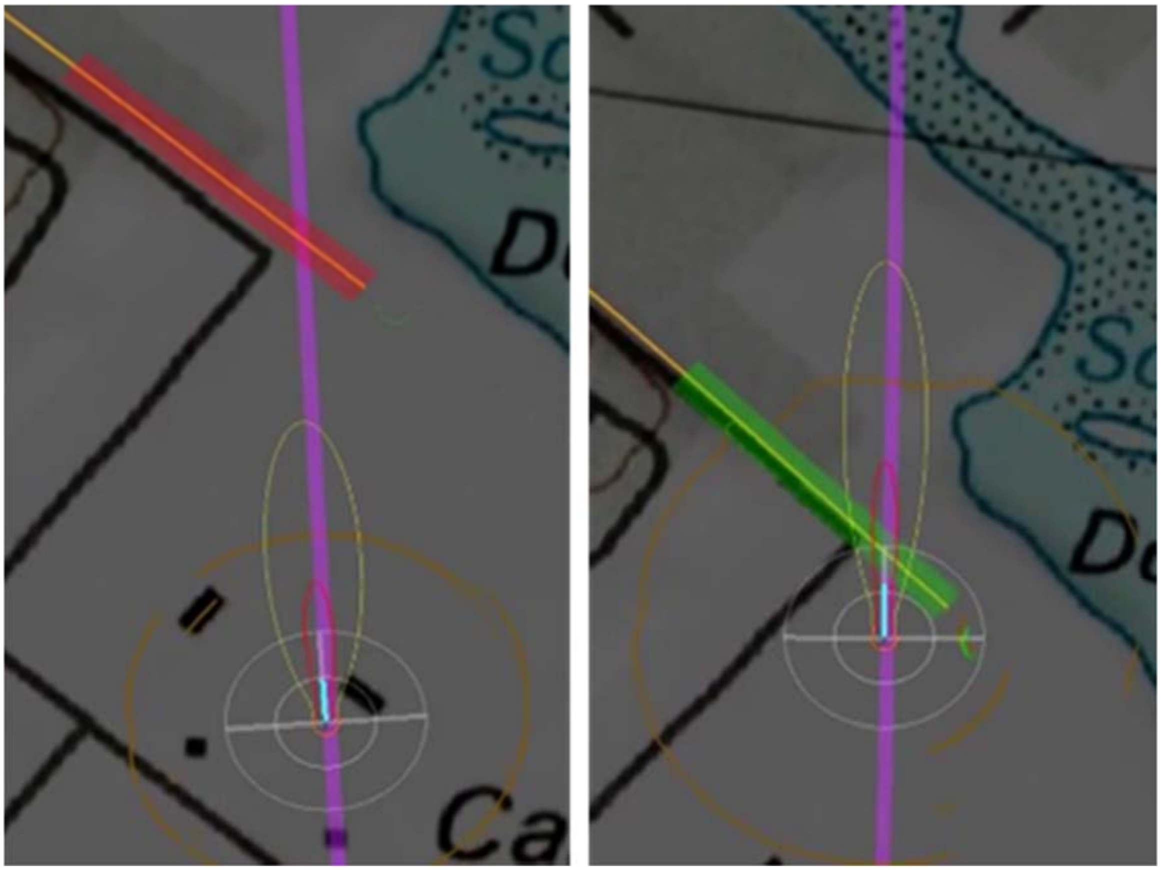


Figure 8. The Integrated Collision Avoidance Display (ICAD) nearest Power Line symbology is red when the ownship is below clearance (left) and green when the ownship has cleared the power line (right). The power line flashes slightly transparent/opaque at 1.5 Hz when not cleared to capture the pilot's attention.

The ICAD and ICE-CAS displays are shown together in Figure 9. Note, the PMD display elements for the most urgent obstacle (diamond) and the ICE-CAS flight path marker (cyan circle) are essentially cross sections of the ICAD most urgent obstacle vector and velocity vector. For example, during level flight, there is a heading and Earth-orthogonal viewport in the ICAD scene through which the pilot views the right image. In this way, a tight coupling exists between 2.5D and 3D display elements.

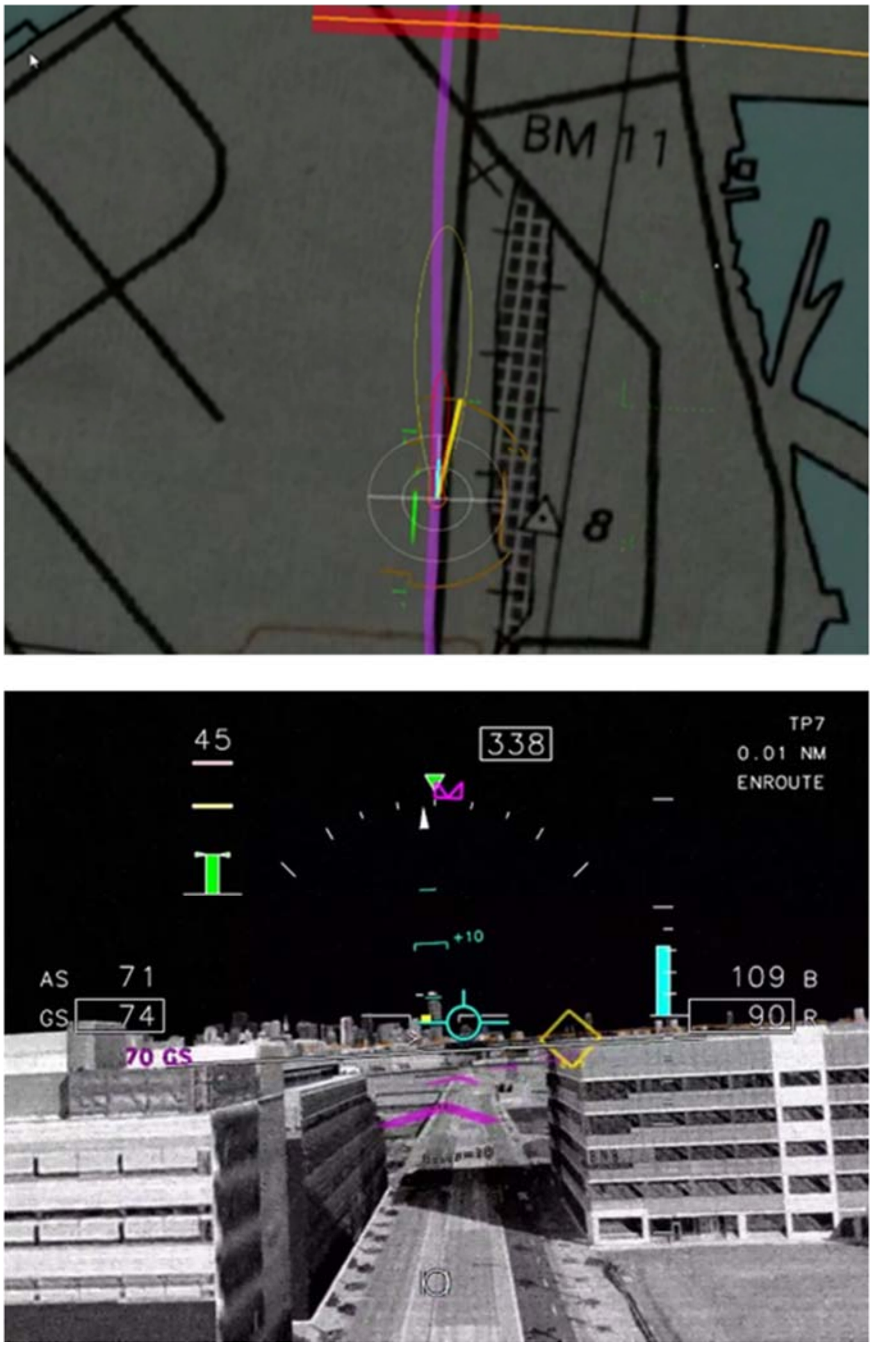


Figure 9. Top: the Integrated Collision Avoidance Display (ICAD) 2.5D and Bottom: Integrated Cueing Environment-Collision Avoidance System (ICE-CAS) 3D Panel Mounted Displays (PMD) demonstrating paired symbology for: (1) the most-urgent obstacle shown as an ICAD obstacle vector and ICE-CAS diamond, both colored according to threat level (Caution in this example), (2) the nearest power line segment shown by the ICAD clearance indicator (red indicating below clearance) and ICE-CAS conformal dashed line (orange indicating below clearance), (3) the ICAD 2.5D velocity vector (cyan line) and ICE Flight Path Marker (cyan circle).

Augmented Reality Spatial Auditory Display (ARSAD).

The ARSAD sonifications were developed using the slab3d-based AvADE Aviation Auditory Display Engine (Miller, Godfroy-Cooper, & Wenzel, 2018; Miller & Wenzel, 2002). The slab3d-based display (http://slab3d.sonisphere.com/) is an Open-Source real-time virtual acoustic environment rendering system developed and used by NASA Ames Advanced Controls and Displays (ACD), AFRL Battlespace Acoustics, and the Army Aviation Development Directorate - Ames. AvADE adds spatial sonification support and provides a server for simulator integration. The ARSAD sonifications are described in detail in (Miller, Godfroy-Cooper, & Wenzel, 2018; Godfroy-Cooper, Miller, Bachelder, & Wenzel, 2018; Miller, Godfroy-Cooper, & Szoboszlay, 2019).

The sonifications were presented via communications earplugs (CEPs) developed by the U.S. Army Aeromedical Research Laboratory (USAARL) at Ft Rucker, Alabama (Ahroon, Gordon, Mozo & Katz, 2000) that were worn in combination with the standard Helmet General Use–56/Personal (HGU-56/P) rotary wing aircrew helmet (Gentex - Corporate Headquarters, 324 N. Main Street, Carbondale, PA 18407 Phone: 570-282-8512).

Sonification mappings.

Obstacle urgency to earcons.

Blattner et. al. (1989) proposed an approach to construct earcons, and earcon families, based on the musical qualities of auditory information. For the obstacle sonification, the two most urgent obstacle hits were identified by two unique spatial earcons, termed “Urgent 1” for the most-urgent obstacle and “Urgent 2” for the second-most urgent obstacle, mapping urgency to timbre and pitch. The Urgent 1 earcon sounded slightly higher in pitch and harsher in timbre relative to the Urgent 2 earcon. The details of the sound design are discussed in (Miller, Godfroy-Cooper, & Wenzel, 2018).

Obstacle location to augmented-reality display location.

Given that obstacle locations were presented using an augmented-reality display, obstacle location was mapped to the acoustic model parameters of azimuth, elevation, and distance relative to the listener. Azimuth and elevation were implemented via Head Related Transfer Function (HRTF) indexing and interpolation, and range via a spherical-spreading loss gain model (see Figure 10).

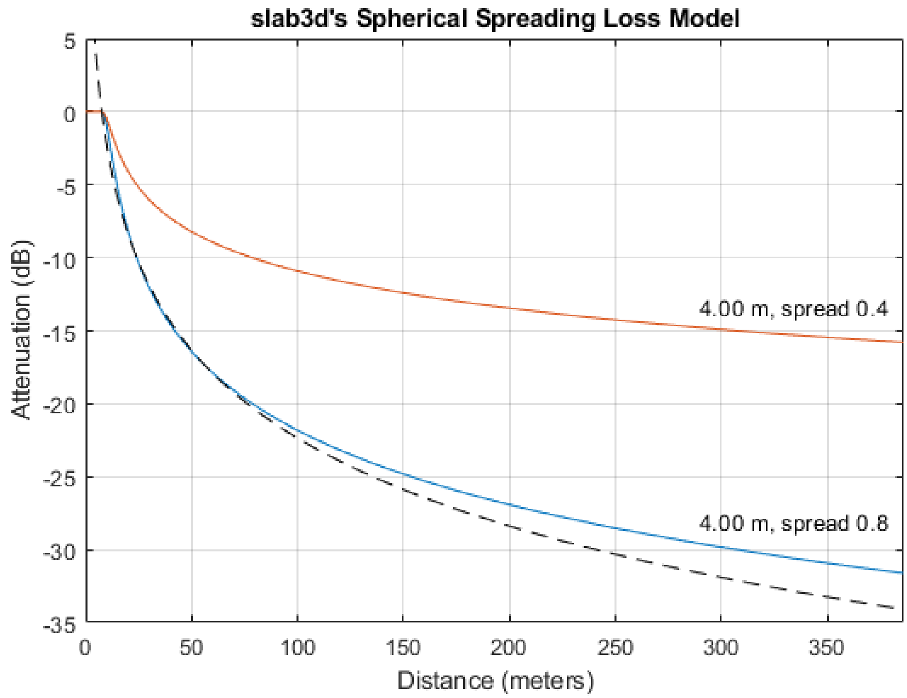


Figure 10. The Obstacle (top) and Power Line (bottom solid) Looming Effects implemented via slab3d's source-listener distance gain model with a 0-dB reference at the helicopter blade radius of 27 ft (8.2 m).

Obstacle azimuth to pitch scaling.

To accentuate obstacle azimuth angle relative to ownship and to reduce front-back reversal (i.e. source localized to the incorrect front-back hemifield) a Sonifier "Pitch Scaling" algorithm was developed. Inspired by HRTF head and pinna shadowing (a filtering of the sound due to the head and pinna's obstruction of high frequencies for rear-incident sources), the Sonifier reinforced HRTF shadowing when the pilot is looking forward. Eight azimuth pie slices were used to decrease earcon pitch 40 cents per slice, front-to-back (Figure 11). Since the pitch scaling was performed relative to ownship, the pitch remained unchanged with head-tracked head motion.

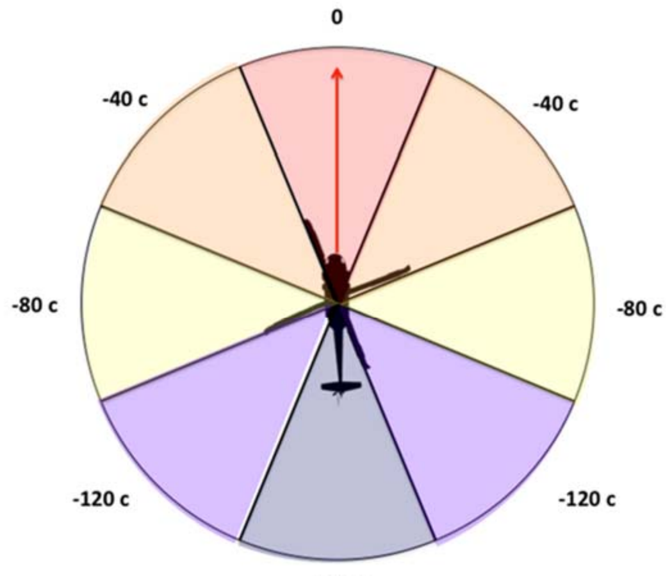


Figure 11. Obstacle-Ownship azimuth pie slices for sonifier earcon pitch scaling. It was designed to reduce the occurrences sources localized to the incorrect front-back hemifield (front-back reversal).

Dynamic obstacle range to looming effect.

Visual looming refers to the rate of change in the size of an approaching object's retinal image. A corresponding auditory "Looming Effect" occurs with an oncoming sound's increase in intensity over time. Therefore, it is advantageous for a visual object's sonification to share an overall stimulus energy profile with the visual object (when visible). This was provided by slab3d's distance-based gain model as shown in Figure 10.

Obstacle range to pulse period.

Patterson (1982) and Edworthy et al. (1991) stated that temporal aspects are critical in distinguishing between sounds, and pulse rate is probably the strongest influence on perceived urgency. Later work by Brewster (1994) showed that rhythm and tempo variations (i.e., speeding up or slowing down pulse patterns) are an effective method for differentiating earcons. The pulse parameters used were based on the work of Hellier et al. (1993), who used a 200 ms tone with inter pulse intervals ranging from 9 to 475 ms (i.e., pulse rates of 1.5 - 4.8Hz). Small pulse durations (< 80 ms for complex and < 30 ms for simple earcons) decrease perception and should be avoided (Brewster, Wright, & Edwards, 1995). Given that pilots were already accustomed to the pulse-period collision indicators provided in some modern vehicles, pulse period was selected for sonifying distance.

Between the Caution and Warning maximum extents, the Obstacle sonification used complex tone pulses 80 ms in duration with an inclusive fade in and out of 30 ms. The low-speed obstacle-ownship range mapping consists of a range-to-pulse period maximum distance of 80 ft for Caution and 37 ft for Warning with the pulse period linearly scaled 2000 ms (½ Hz) to 250 ms (4 Hz) between them. If the range is under the maximum Warning extent, the pulse period remains a constant 250 ms, whereas the pulse duration doubles to 160 ms, such that when in the Warning region, the duration of the pulses were longer. If the obstacle was outside of the Caution region, the sonification was muted. At speeds above the Fixed-Distance Threshold (7.3 knots), the maximum distance is based on time to collision (TTC) and ownship speed with a Caution TTC of 6.5 secs and a Warning TTC of 3.0 secs. The maximum distances occur in the direction of the velocity vector.

Power line sonification.

The Power Line sonification used a recording of a power line (Blume, 2012) as a spatial auditory icon (a sound representing the object to which it is referring). The sonification's augmented-reality virtual emitter was swept up and down the power line at a rate of 100 ft/sec. The nearest power line segment in the terrain database was found with the closest point chosen as the central location from which to sweep 33 ft on either side. Although this yields a travel frequency of 0.76 Hz, an audible pulse was detected with the end-to-end sweep and direction change, yielding an audible pulse frequency of 1.5 Hz. For a perpendicular approach and a constant sweep extent, the perceived spatial extent increases as the pilot approaches the power line (Figures 12a and 12b), like how it appears visually. For a parallel heading (Figure 12c), the sonification's relative center point remains fixed and produces a longitudinal (front-back) sweep.

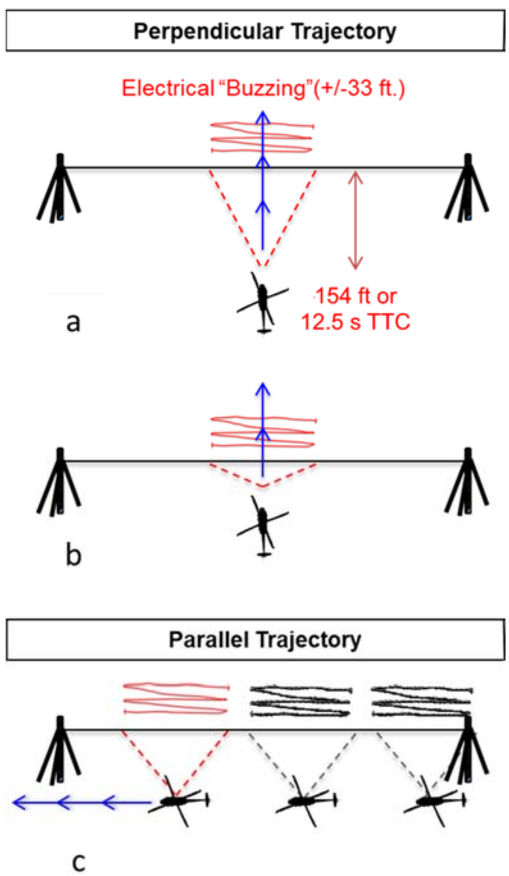


Figure 12. The Power Line sonification behavior for a perpendicular (a and b) and parallel (c) trajectory relative to the wires. The sonification enables at 154 ft below 7.3 knots and 12.5 s TTC above 7.3 knots.

Like the Obstacle sonification, the Power Line sonification was in a fixed-distance mode below the Threat Assessment Fixed-Distance Threshold (360 SA default 7.3 knots) and a TTC mode above (TTC 12.5 seconds). This resulted in the sonification activation at 154 ft from the blades at low speeds and at 12.5 seconds from contact at higher speeds. This yielded a cylindrical Caution region with a varying radius centered on a line between the nearest two towers.

Whenever the helicopter was in this region, the sonification was audible with the distance-dependent gain profile shown in Figure 10. Thus, the Power Line sonification maps obstacle location to the augmented-reality location, and dynamic ownship-obstacle range to the auditory Looming Effect. Note, the Power Line does not have an explicit Warning region. However, as the power line nears, the gain slope relative to distance increases significantly, creating a very noticeable and pronounced Looming Effect.

Tactile Situational Awareness System (TSAS).

The Tactile Situational Awareness System (TSAS) manufactured by Engineering Acoustics, Inc. consists of a belt, shoulder strap, and seat pan tactors (Figure 13). The belt is equipped with 12 tactors equally distributed about the waist, 0° forward to 330° in 30° increments. When the most urgent obstacle enters the Warning region, a vibration emanates from the direction of the detected obstacle. The shoulder straps indicate that the altitude has exceeded the recommend height and matches the ICE monaural cue “radar tracking”. The seat pan indicates excessive downward speed and matches the ICE monaural cues “vertical speed excessive” and “pull-up”. For the 12-tactor belt, the azimuth of the most urgent obstacle is mapped to a tactor using 30° angular regions centered at the tactors (i.e., 12 pie slices). The tactile Warning pulse period matches the Obstacle sonification Warning pulse period of 250 ms. However, the pulse duration is slightly slower at 100 ms (versus auditory 160 ms) in order to preserve the impulsiveness of the tactor. The tactors were set to full amplitude gain.

Figure 13. The Tactile Situational Awareness System (TSAS). The belt provides obstacle cueing from 12 directions, 0° forward to 330° in 30° increments.

Integrated Trimodal and Layered Approach.

The visual, spatial auditory, and tactile displays were structured such that Cautions and Warnings occured in a “layered approach” where the visual display provided cueing before or simultaneously with the spatial auditory display which, in turn, cued before or simultaneously with the tactile display (Figure 14).

The logic behind a layered approach is complementarity rather than redundancy, at least for the auditory and tactile components of the display. For example, the belt tactors represent the “ultimate” obstacle warning after the visual and auditory warnings failed to correct the pilot’s obstacle avoidance trajectory. This sequential rather than parallel presentation mode was selected to reduce the potential workload resulting from the division of attention between the different sensory modalities. It also mimicked the natural order in which the different modalities are usually perceived in ecological conditions, where tactile cueing is restricted to the peripersonal space (space immediately surrounding the body, ~70 cm in humans).

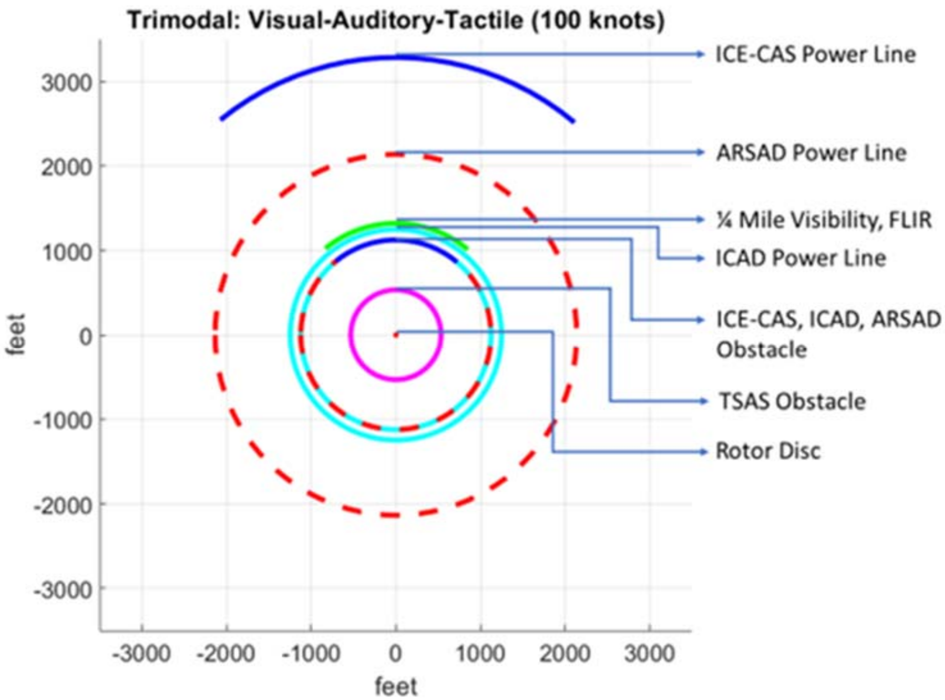
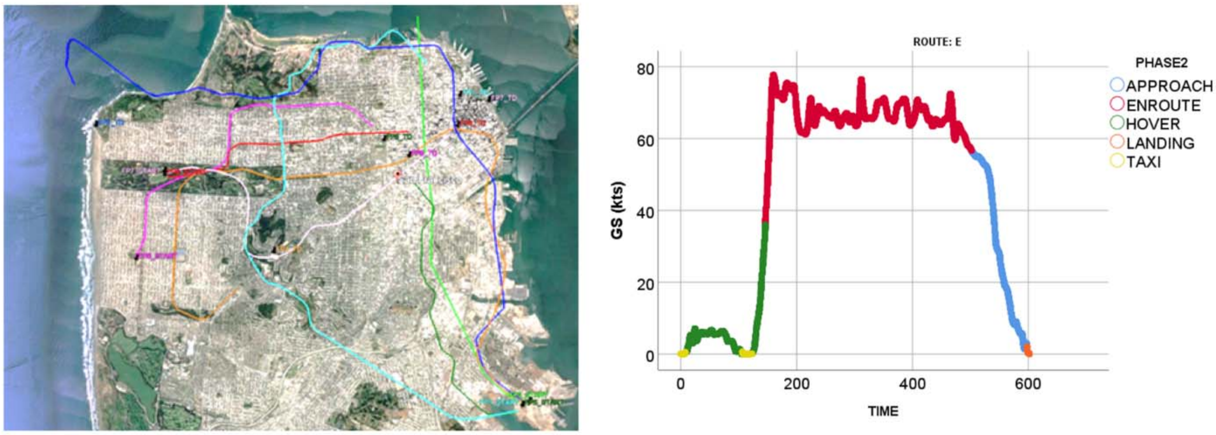


Figure 14. The 360° Situational Awareness trimodal Visual-Auditory-Tactile display layered approach shown in distance and bearing angle for an ownship speed of 100 knots heading-up. In general, the cueing for a RADAR-detected Obstacles or database Power Lines was ordered: Visual before or at the same time as Auditory, Auditory before or at the same time as Tactile. ICE-CAS elements are shown as solid blue arcs, ICAD elements as solid cyan circles, ARSAD elements as dashed red circles, and TSAS as a solid magenta circle. The rotor disc is at the origin.

Mission Profile

Ten flight vignettes were created for this study using a database based on San Francisco, developed by PLW Modelworks LLC. Two additional vignettes were used for the training flights. All of the mission scenarios, other than those used for training, were of similar length of time. However, the number, location, and type of obstacles differed, so that pilots would not become familiarized with the presence of obstacles. This required the pilots to rely on the use of the cueing to detect and avoid obstacles. Each trial flight included the flight maneuvers described in the following section.



A. B.

Figure 15. A. Mission Routes in the San Francisco Bay Area. B. Flight Tasks for Route E, Pilot 6. From start to end: Taxi, Takeoff to Hover, Taxi, Takeoff to Hover, En-route, Approach and Landing. Vertical axis: Ground Speed (GS, knots).

Flight Maneuvers

The pilots completed standard maneuvers through each segment of each flight. These maneuvers included: taxi, takeoff, en-route, approach, and landing. Table 3 below summarizes the start and end points for data collection within each maneuver.

Taxi.

This task began with the aircraft ground-taxiing at a specified low speed around the runway or in an urban environment. When the aircraft cleared any obstacles, the pilot was required to ascend to a specified altitude of 10 ft and accelerate to a specified airspeed (e.g., 7 knots).

Takeoff.

This task began once the aircraft reached the takeoff location at the completion of the ground-taxi maneuver. The aircraft then conducted a takeoff from the ground.

En-route.

This task was initiated with the aircraft traveling on an established flight path moving at a specified airspeed and altitude toward the approach point. During this maneuver the aircraft transitioned in and out of DVE environments (i.e., transition from visual flight rules (VFR) flight into DVE and back to VFR).

Approach.

This task started with the aircraft at a specified altitude and moving at a specified airspeed toward the landing point. Descent from altitude began at a specified distance from the landing point.

Landing.

This task began when the pilot lowered the aircraft to the ground and all wheels were on the ground or the altitude was below 10 ft.

Table 3. Maneuver Definitions within Data

Maneuver	Start	End
Taxi	Aircraft ground taxis to takeoff start point	When takeoff point reached and aircraft lifts to 10ft hover.
Takeoff	When symbology takeoff mode/waypoint type is set	Upon reaching start of waypoint
En-route	Upon reaching start of waypoint	0.8 NM from landing point
Approach	0.8 NM from landing point	1) Any aircraft wheels touch the ground OR 2) Hover begins
Landing	1) When all wheels are on ground OR 2) Radar altitude is < 10 ft and simulator crash flag is set OR 3) Research pilot advances waypoint to command pilot to hover down to landing point	After 2 s with ALL wheels on the ground

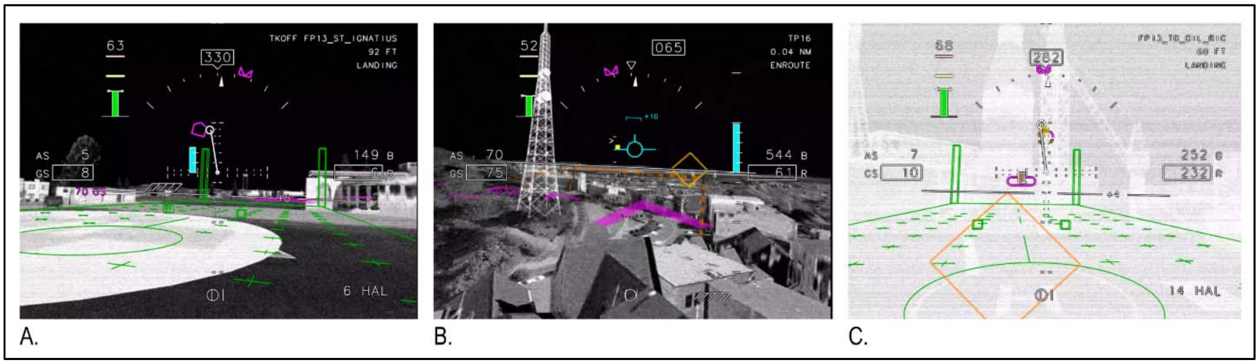


Figure 16. From Left to Right: ICE-CAS Takeoff to Hover Page, ICE-CAS Enroute Page and ICE-CAS Landing Page.

Flight Performance Metrics

Simulator data were recorded at a rate of 60 Hz during data acquisition. After data acquisition, a post-processing script was applied to the 60 Hz time series data to extract the metrics for the study. Metrics were derived for each phase of flight (taxi, takeoff, en-route, approach, and landing) for each flight condition. To evaluate occurrences of proximity to obstacles we examined both the length of time spent within the threat level space within the Caution and Warning spaces, as defined above. Frequency of soft and hard crashes, when available, were also analyzed. See Table 4 for definitions of metrics and phase of flight collected.

Table 4. Flight Metric Definitions.

Metric	Definition	Phase of Flight
Time within Caution Threat Level Region (TL >0.0 to <0.54)	Time spent within Caution Region – nearest one obstacle (Urgent 1) or nearest two obstacles (Urgent 1 and 2) presented	Taxi, Takeoff, En-Route, Approach, Overall Flight
Time within Warning/Rotor Threat Level Region (0.54 to 1.0)	Time spent within Warning Region – nearest one obstacle (Urgent 1) or nearest two obstacles (Urgent 1 and 2) presented	Taxi, Takeoff, En-Route, Approach, Overall Flight
Soft Crash	Frequency of when the aircraft clipped trees or other obstacles	Taxi, Takeoff, En-Route, Approach, Overall Flight
Hard Crash	Frequency of when aircraft crashed completely	Taxi, Takeoff, En-Route, Approach, Overall Flight
Landing Deviations	Radial errors at touchdown	Landing

Subjective Metrics

Following completion of flight tasks for each cueing set combination, subjective measures were completed to assess the impact of the cueing modalities on each pilot's workload, motion sickness, situation awareness, and usability and trust of the cueing. The following measures were used: the Bedford Workload Rating Scale (Roscoe, 1984) (see Appendix A), Motion Sickness Assessment Questionnaire (Ginaros, Muth, Mordkoff, Levine, & Stern, 2001); Situation Awareness Rating Scale (developed by Data and Analysis Center); Cueing Usability Questionnaire (developed by Data and Analysis Center); and Trust in Automation questionnaire (developed by Data and Analysis Center). At the end of all testing, the pilots completed a lengthy in-house developed post-test Cueing Usability Questionnaire, training effectiveness questionnaire and ranked their cueing preferences. The pilots also participated in an after-action review (AAR) where comments were recorded to gain additional impressions of the cueing. All subjective questionnaires were presented to pilots on a tablet computer.

Results

Results of the study are reported below for flight performance by phase of flight, summary of all phases combined, and summary of crashes. Subjective results are reported by questionnaire. Below includes the results relevant to obstacle avoidance (e.g., Time spent within the Threat Space), as its evaluation was a main goal of the study. However, pilots' qualitative responses (Appendix D), and biometric data (Appendix C) are reported within the appendices.

Flight Performance

The average percentage of time the helicopter spent within the Caution Region with each one obstacle present (Urgent 1) and two obstacles present (Urgent 1 and Urgent 2), and within the Warning/Rotor Region with each one obstacle present (Urgent 1) and two obstacles present (Urgent 1 and Urgent 2) during each phase of flight were calculated as a function of the Configuration, the Route of Flight, and a combination of Configuration x Route of Flight. Although configuration was the main factor of interest in this study, flight route was a confounding variable and a greater contributor to the overall variation in the time spent within a threat level region during each phase. Any comparison across configurations must take into account the flight route. In order to compare performance in the BL configuration to each of the other four configurations, where possible, linear mixed effects models were developed with and without configuration as a regressor. Configuration and route of flight were considered fixed effects and subject intercept was a random effect. Likelihood ratio tests were run to contrast the full model with the configuration effect to the partial model without the configuration effect.

Additionally, to examine the possible benefits of the layered cueing approach used, additional comparisons were made for each threat space region (Caution, Warning/Rotor) and obstacle combination (Urgent 1, Urgent 1 and 2). Specifically, since the TSAS does not activate in the Caution region, data from configurations were combined to form three cueing categories. The data from the V and VT configurations were combined to form a cueing category labeled V+VT. The data from the VA and VAT configurations were combined to form a cueing category labeled VA+VAT. The data from the baseline configuration formed a cueing category labeled BL. The following three pairwise comparisons of the percentages of time spent in the Caution Region were conducted: BL vs V+VT, BL vs VA+VAT, and V+VT vs VA+VAT. Since TSAS does activate when in the Warning/Rotor region, pairwise comparisons of the following configurations were conducted in the Warning/Rotor region of the Threat Space.

Finally, in reviewing the results, please note that summary statistics in some phases of flight may appear to contradict the descriptive statistics reported within the tables. This contradiction is a product of the unbalanced design of the experiment. In particular, the number of times each route was flown varied across the configurations. Specifically, a close inspection of the baseline and visual + audio + tactile (VAT) configurations shows that they only had five of the 10 routes in common.

Taxi Performance

Percentage of Time within the Caution Region during Taxi.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with one obstacle present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 17).

Visual examination of the graph on the left suggests that significantly less time was spent in the Caution Region with Urgent 1 obstacle present during BL configuration flights. Given the differences in routes, a heat map was produced to visually depict overlap in common routes. A comparison of VAT to BL performance, using the heat map on the right, shows that percentage of time spent within the Caution Region with Urgent 1 obstacle present when flying the VAT configuration was greater than BL on three of the five routes they had in common.

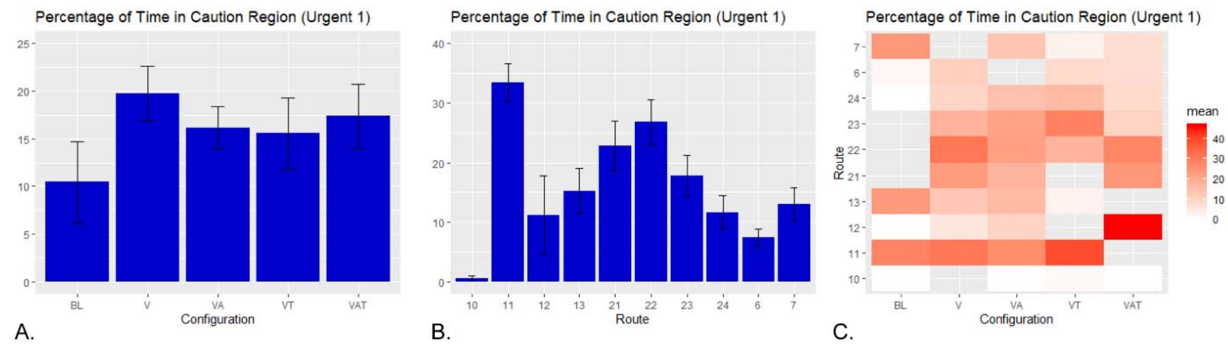


Figure 17. A: Taxi Time Spent within the Caution Region with Urgent 1 obstacle present by Configuration. B: Taxi Time Spent within the Caution Region with Urgent 1 obstacle present by Route. C: Taxi Heat Map of Percentage Time Spent within the Caution Region with Urgent 1 obstacle present by Route and Configuration.

Results of the linear mixed effects models found configuration did not have a statistically significant effect on the percentage of time spent within the Caution Region with Urgent 1 obstacle present, $\chi2$ (4) = 1.46, $p = 0.83$. The percentages of time spent within the Caution Region with Urgent 1 obstacle present were statistically equivalent for all configurations during the taxi phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the taxi phase.

One Obstacle Present – Comparison of Baseline, Visual, and Audio.

The percentages of time spent within the Caution Region with Urgent 1 obstacle present were statistically equivalent in the BL cueing category and in both the V+VT cueing category, $F(1, 38) = 1.01$, $p = 0.322$, and the VA+VAT cueing category, $F(1, 32) = 3.14$, $p = 0.086$. The percentages of time spent within the Caution Region with Urgent 1 obstacle present were statistically equivalent in the V+VT cueing category and in the VA+VAT cueing category, $F(1, 60) = 0.14$, $p = 0.714$. See Table 5 for descriptive statistics.

Table 5. Descriptive Statistics—Time in Caution Region with Urgent 1 Obstacle Present

Cueing Category	Mean	SE
BL	10.46	4.24
V+VT	17.69	2.34
VA+VAT	16.74	1.99

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 18).

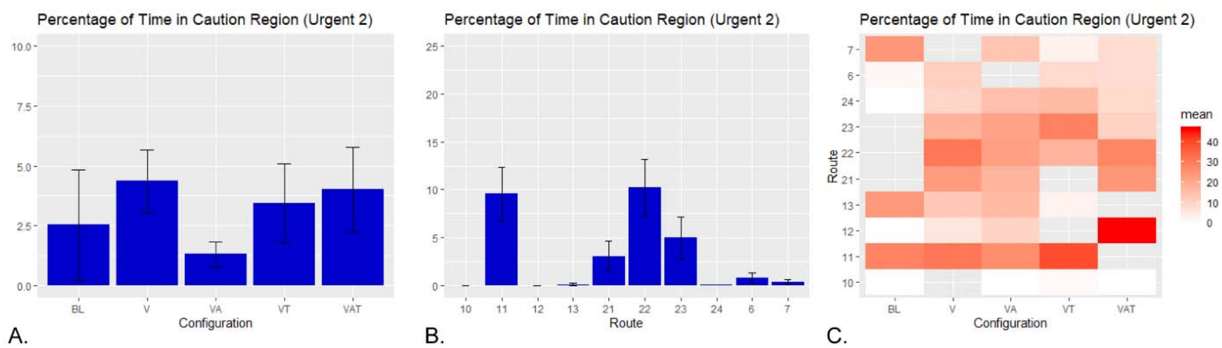


Figure 18. . A: Taxi Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Configuration. B: Taxi Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Route. C: Taxi Heat Map of Percentage Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Route and Configuration.

In 54 of the 89 flights during the taxi phase, 60.7% of flights, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provides no evidence that configuration had a significant effect. The percentages of time within an the Caution Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all configurations during the taxi phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the taxi phase.

Two Obstacles Present – Comparison of Baseline, Visual, and Audio.

Given that in 60.7% of flights, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that cueing category had a significant effect. The percentages of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all three cueing categories (see Table 6 below).

Table 6. Percentages—Time in Caution Region with Urgent 1 Obstacle Present

Cueing Category	Mean	SE
BL	2.54	2.31
V+VT	3.91	1.04
VA+VAT	2.67	0.94

Percentage of Time within the Warning/Rotor Region during Taxi.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 obstacle present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 19).

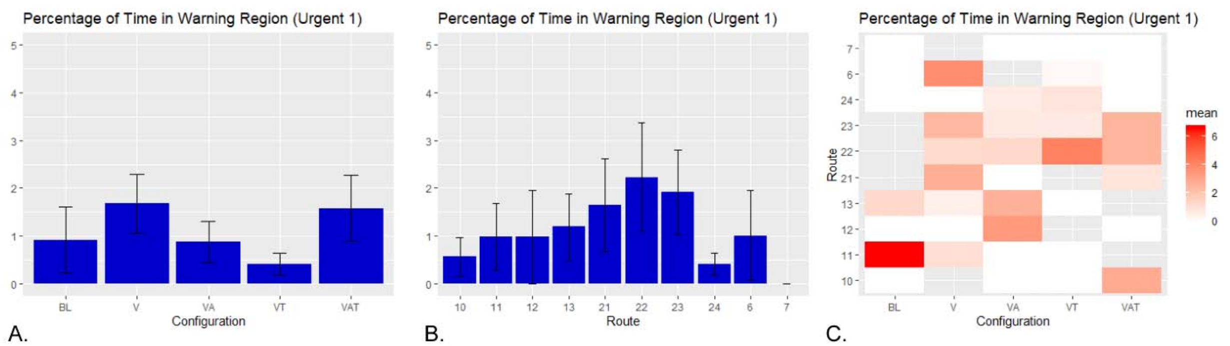


Figure 19. A: Taxi Time Spent within the Warning/Rotor Region with Urgent 1 obstacle present by Configuration. B: Taxi Time Spent within the Warning/Rotor Region with Urgent 1 obstacle present by Route. C: Taxi Heat Map of Percentage Time Spent within the Warning/Rotor Region with Urgent 1 obstacle present by Route and Configuration.

In 60 of the 89 flights during the taxi phase, 67.4% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 obstacle present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 obstacle present were equivalent for all configurations during the taxi phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the taxi phase.

One Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

Given that in 67% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 obstacle present during the taxi phase, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and obstacle present during the taxi phase were equivalent for all configurations. See table 7 for descriptive statistics.

Table 7. Percentages—Time in Warning/Rotor Region with Urgent 1 Obstacle Present

Cueing Category	Mean	SE
V	1.68	0.43
VT	0.41	0.68
VA	0.87	0.43
VAT	1.59	0.68

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present were first plotted to visually inspect distribution of time across each of the configurations (see Figure 20).

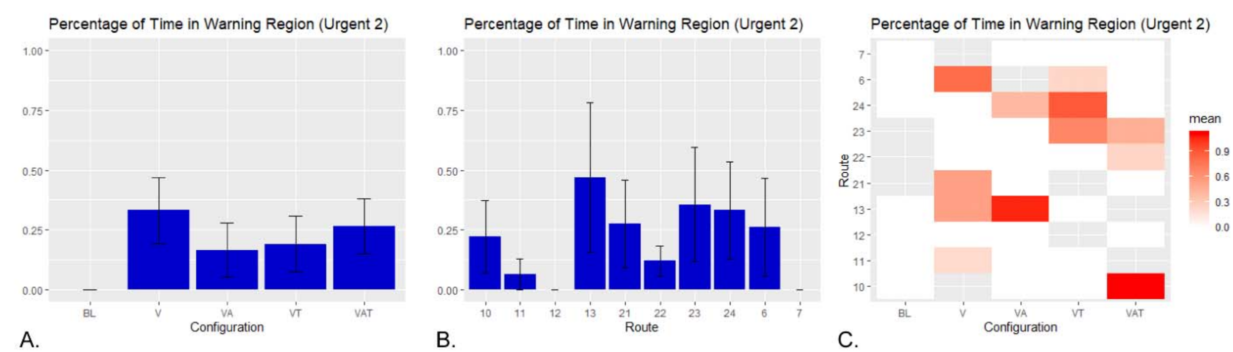


Figure 20. A: Taxi Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Configuration. B: Taxi Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Route. C: Taxi Heat Map of Percentage Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Route and Configuration.

In 72 of the 89 flights during the taxi phase, 80.9% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present. The high number of “zero” data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within an the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all configurations during the taxi phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the taxi phase.

Two Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

Given that in 81% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the taxi phase it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the taxi phase were equivalent for all configurations. See Table 8 below.

Table 8. Percentages—Time within Warning/Rotor Region with Two Obstacles Present

Cueing Category	Mean	SE
V	0.33	0.14
VT	0.19	0.12
VA	0.17	0.11
VAT	0.26	0.11

Takeoff Performance Data

Percentage of Time within the Caution Region during Takeoff.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with Urgent 1 obstacle present was first plotted to visually inspect distribution of time across each of the configurations. Visual examination of the graph on the left suggests that significantly less time was spent within the Caution Region with Urgent 1 obstacle present during VAT configuration flights. Given the differences in routes, a heat map was produced to visually depict overlap in common routes. A comparison of VAT to BL performance, using the heat map on the right, shows that during VAT configurations, proximity to obstacles, measured by time spent within the Caution Region, was only better (i.e., less time spent within region) than BL on one of the five routes they had in common.

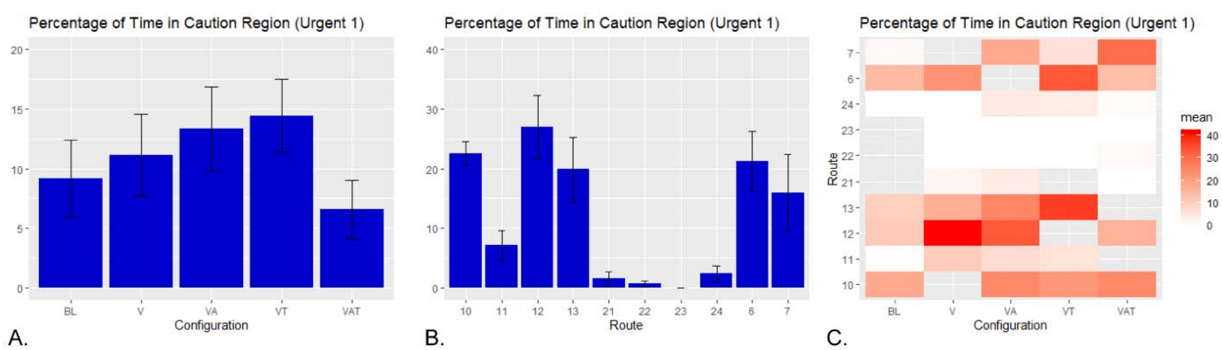


Figure 21. A: Takeoff Time Spent within the Caution Region with Urgent 1 obstacle present by Configuration. B: Takeoff Time Spent within the Caution Region by Route with Urgent 1 obstacle present. C: Takeoff Heat Map of Percentage Time Spent within the Caution Region with Urgent 1 obstacle present by Route and Configuration.

Results of the linear mixed effects models found configuration had a statistically significant effect on the percentage of time spent within the Caution Region with Urgent 1 obstacle present, χ^2 (4) = 17, $p < 0.05$. A post hoc analysis of the various configurations revealed the following:

Percentage of time within the Caution Region with Urgent 1 obstacle present was significantly higher compared to the BL configuration in each V configuration, t (11.95) = 2.431, $p < 0.05$, VA configuration, t (12.09) = 2.851, $p < 0.05$, and VT configuration, t (14.18) = 3.064, $p < 0.05$. There was no difference in the percentages of time spent within the Caution Region with Urgent 1 obstacle present during VAT configuration and BL configuration flights, t (15.43) = 1.624, $p > 0.05$.

One Obstacle Present – Comparison of Baseline, Visual, and Audio.

The percentage of time spent within the Caution Region with Urgent 1 obstacle present was higher in the V+VT cueing category than in the BL cueing category, $F(1, 29) = 12.99$, p = 0.001, and slightly higher in the VA+VAT cueing category than in the BL cueing category, $F(1, 31) = 6.87$, $p = 0.013$. The percentages of time spent within the Caution Region with Urgent 1 obstacle present are statistically equivalent in the V+VT cueing category and in the VA+VAT cueing category, $F(1, 59) = 0.01$, $p = 0.987$. See Table 9 below for descriptive statistics.

Table 9. Percentages—Time in Caution Region with One Obstacle Present

Cueing Category	Mean	SE
BL	9.18	3.19
V+VT	12.71	2.29
VA+VAT	9.96	2.17

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 22).

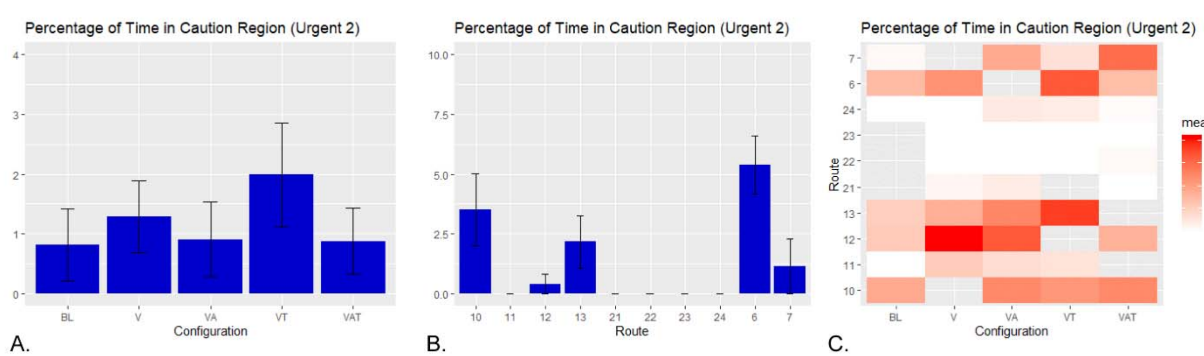


Figure 22. A: Takeoff Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Configuration. B: Takeoff Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Route. C: Takeoff Heat Map of Percentage Time

Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Route and Configuration.

In 72 of the 89 flights during the takeoff phase, 80.9% of flights, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent in the Caution Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all configurations during the takeoff phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the takeoff phase.

Two Obstacles Present – Comparison of Baseline, Visual, and Audio.

Given that in 80.9% of flights, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that cueing category had a significant effect. The percentages of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all three cueing categories. See Table 10 below for descriptive statistics.

Table 10. Percentages—Time in Caution Region with One Obstacle Present

Cueing Category	Mean	SE
BL	0.82	0.60
V+VT	1.63	0.52
VA+VAT	0.89	0.41

Percentage of Time within the Warning/Rotor Region.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 obstacle present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 23).

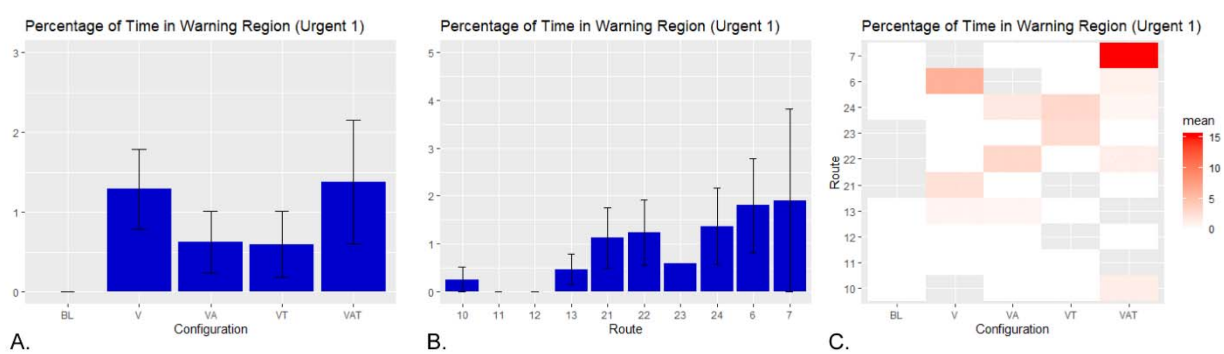


Figure 23. A: Takeoff Time Spent within the Warning/Rotor Region with Urgent 1 obstacle present by Configuration. B: Takeoff Time Spent within the Warning/Rotor Region with Urgent

1 obstacle present by Route. C: Takeoff Heat Map of Percentage Time Spent within the Warning/Rotor Region with Urgent 1 obstacle present by Route and Configuration.

In 72 of the 89 flights during the takeoff phase, 80.9% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 obstacle present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within an the Warning/Rotor Region with Urgent 1 obstacle present were equivalent for all configurations during the takeoff phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the takeoff phase.

One Obstacle Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

Given that in 81% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 obstacle present during the takeoff phase, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and obstacle present during the takeoff phase were equivalent for all configurations. See Table 11 below for descriptive statistics.

Table 11. Percentages— Time in Warning/Rotor Region with One Obstacle Present.

Cueing Category	Mean	SE
V	1.29	0.50
VT	0.60	0.41
VA	0.63	0.39
VAT	1.38	0.77

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 24).

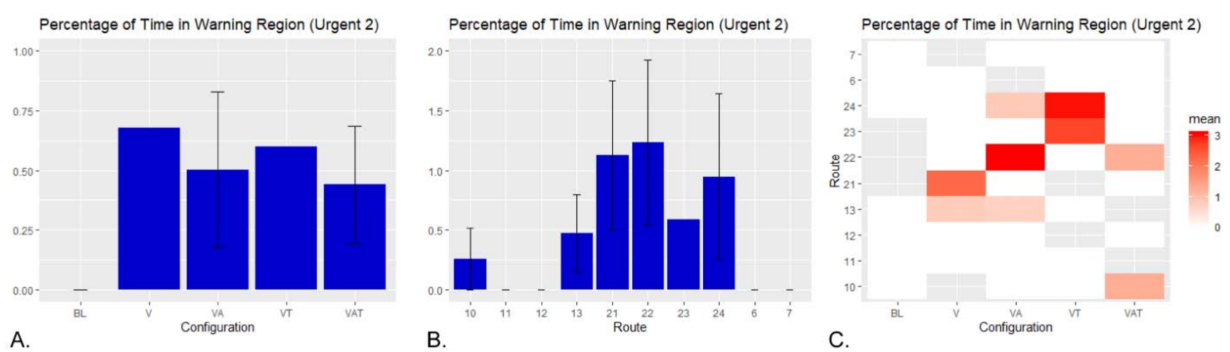


Figure 24. A: Takeoff Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Configuration. B: Takeoff Time Spent within the Warning/Rotor Region

with Urgent 1 and Urgent 2 obstacles present by Route. C: Takeoff Heat Map of Percentage Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Route and Configuration.

In 77 of the 89 flights during the takeoff phase, 86.5% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within an the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all configurations during the takeoff phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the taxi phase.

Two Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

Given that in 87% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the takeoff phase, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the takeoff phase were equivalent for all configurations. See Table 12 below for descriptive statistics.

Table 12. Percentages— Time in Warning/Rotor Region with Two Obstacle Present.

Cueing Category	Mean	SE
V	0.70	0.34
VT	0.60	0.41
VA	0.50	0.33
VAT	0.44	0.25

En-route Performance Data

Percentage of Time within the Caution Region during En-Route.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with Urgent 1 obstacle present were first plotted to visually inspect distribution of time across each of the configurations (see Figure 25). Visual examination of the graph on the left suggests that slightly less time was spent within the Caution Region with Urgent 1 obstacle present during BL configuration flights. Given the differences in routes, a heat map was produced to visually depict overlap in common routes. A comparison of VA to BL performance, using the heat map on the right, shows that BL performance was only better than VA on three of the six routes they had in common.

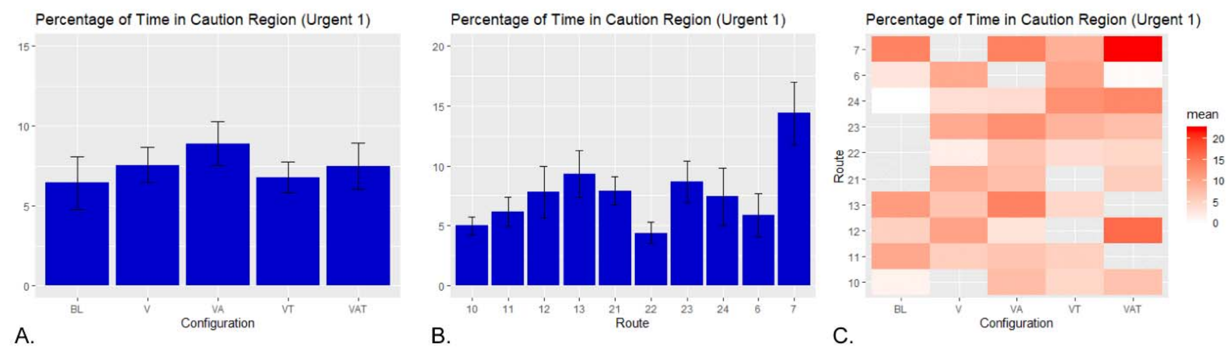


Figure 25. A: Takeoff Time Spent within the Caution Region with Urgent 1 obstacle present by Configuration. B: Takeoff Time Spent within the Caution Region with Urgent 1 obstacle present by Route. C: Takeoff Heat Map of Percentage Time Spent within the Caution Region by Route and Configuration with Urgent 1 obstacle present.

Results of the linear mixed effects models found configuration did not have a statistically significant effect on the percentage of time spent within the Caution Region with Urgent 1 obstacle present, $\chi 2$ (4) = 3.09, p = 0.54. The percentages of time spent within an the Caution Region with Urgent 1 obstacle present were statistically equivalent for all configurations during the en-route phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the en-route phase.

One Obstacle Present – Comparison of Baseline, Visual, and Audio.

The percentages of time spent within the Caution Region with Urgent 1 obstacle present were statistically equivalent in the BL cueing category as with each the V+VT cueing category, $F(1, 29) = 3.74$, $p = 0.063$, the V+VAT cueing category, $F(1, 31) = 0.72$, $p = 0.402$, and the V+VT cueing category and in the VA+VAT cueing category, $F(1, 59) = 0.12$, $p = 0.733$. See Table 13 below for descriptive statistics.

Table 13. Percentages— Time in Caution Region with One Obstacle Present during En-Route

Cueing Category	Mean	SE
BL	6.44	1.64
V+VT	7.17	0.73
VA+VAT	8.17	0.99

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present were first plotted to visually inspect distribution of time across each of the configurations (see Figure 26).

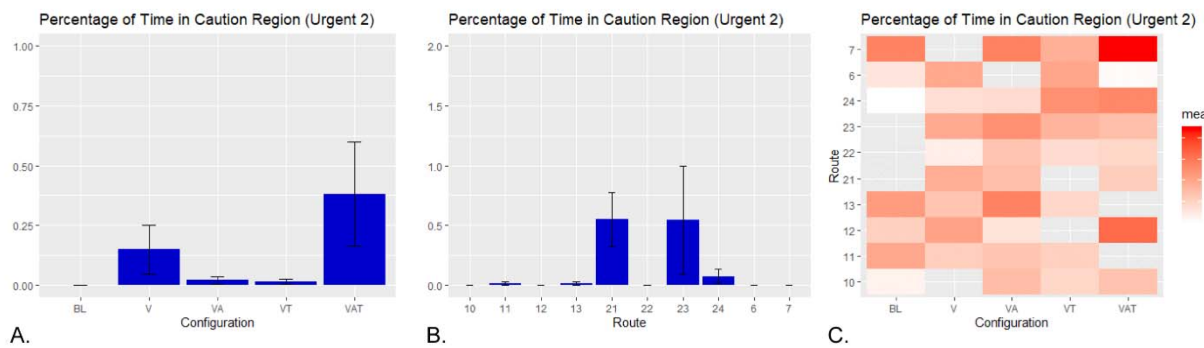


Figure 26. A: En-route Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Configuration. B: En-route Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Route. C: En-route Heat Map of Percentage Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Route and Configuration.

In 77 of the 89 flights during the en-route phase, 86.5% of flights, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within an the Caution Region with Urgent 1 and Urgent 2 obstacles present are equivalent for all configurations during the en-route phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the en-route phase.

Two Obstacles Present – Comparison of Baseline, Visual, and Audio.

Given that in 86.5% of flights, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that cueing category has a significant effect. The percentages of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all three cueing categories. See Table 14 below for descriptive statistics.

Table 14. Percentages— Time in Caution Region with Two Obstacles Present during En-Route

Cueing Category	Mean	SE
BL	0	0
V+VT	0.08	0.05
VA+VAT	0.20	0.11

Percentage of Time within the Warning/Rotor Region during En-Route.

One Obstacle Present – Cueing Configurations Compared to Baseline

The amount of time spent within the Warning/Rotor Region with Urgent 1 obstacle present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 27).

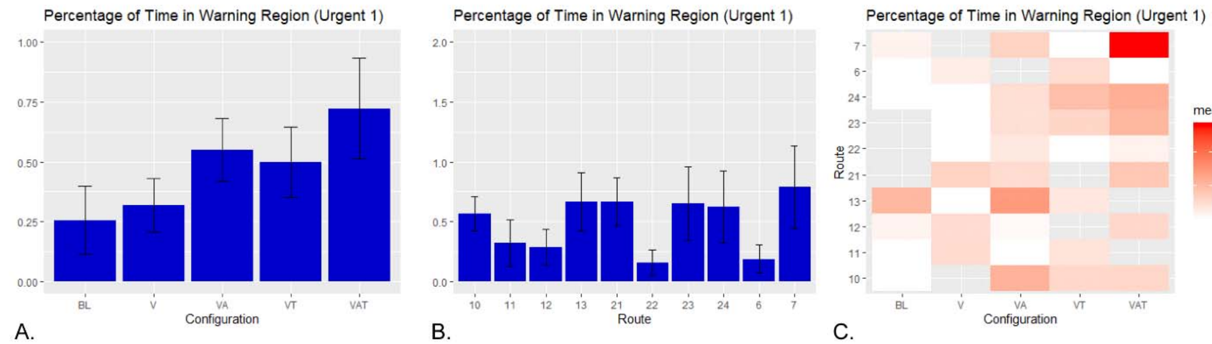


Figure 27. A: En-route Time Spent within the Warning/Rotor Region with Urgent 1 obstacle present by Configuration. B: En-route Time Spent within the Warning/Rotor Region with Urgent 1 obstacle present by Route. C: En-route Heat Map of Percentage Time Spent within the Warning/Rotor Region with Urgent 1 obstacle present by Route and Configuration.

Results of the linear mixed effects models found configuration did not have a statistically significant effect on the percentage of time spent within the Warning/Rotor Region with Urgent 1 obstacle present, $\chi^2(4) = 6.97$, $p = 0.14$. The percentages of time spent within the Warning/Rotor Region with Urgent 1 obstacle present were statistically equivalent for all configurations during the en-route phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the en-route phase.

One Obstacle Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

The percentages of time spent within the Warning/Rotor Region with Urgent 1 obstacle present were statistically equivalent in each of the following comparisons: the V and VT configurations, $F(1, 23) = 2.72$, $p = 0.113$; the VA and VAT configurations, $F(1, 24) = 1.09$, $p = 0.307$; the V and VA configurations, $F(1, 22) = 1.72$, $p = 0.204$; and the VT and VAT configurations, $F(1, 21) = 1.06$, $p = 0.316$. See Table 15 below for descriptive statistics.

Table 15. Percentages— Time in Warning/Rotor Region with One Obstacle Present during En-Route

Cueing Category	Mean	SE
V	0.32	0.11
VT	0.50	0.15
VA	0.55	0.13
VAT	0.72	0.21

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 28).

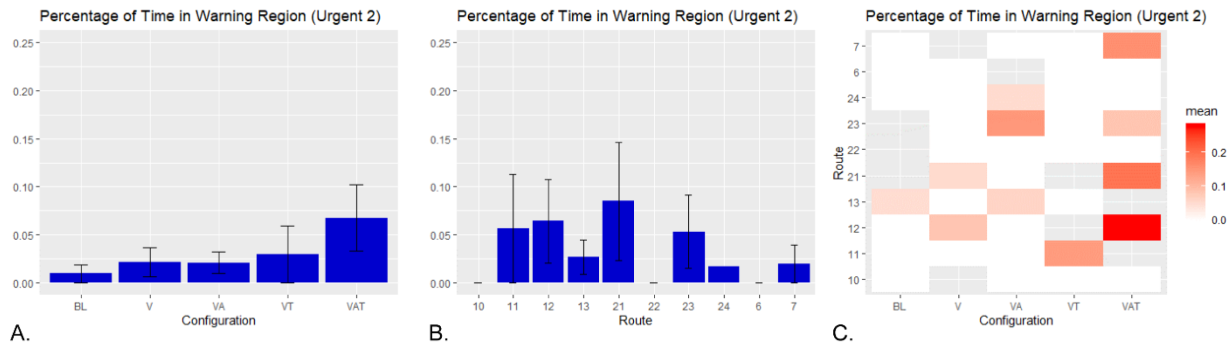


Figure 28. A: En-route Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Configuration. B: En-route Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Route. C: En-route Heat Map of Percentage Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Route and Configuration.

In 78 of the 89 flights during the en-route phase, 87.6% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all configurations during the en-route phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the en-route phase.

Two Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

Given that in 87.6% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the en-route phase, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provides no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the en-route phase were equivalent for all configurations (Table 16).

Table 16. Percentages—Time in Warning/Rotor Region with Two Obstacles Present during En-Route

Cueing Category	Mean	SE
V	0.02	0.02
VT	0.03	0.03
VA	0.02	0.01

VAT	0.07	0.03

Percentage of Time within the Caution Region during Approach.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with Urgent 1 obstacle present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 29). Visual examination of the graph on the left suggested that significantly more time was spent in the Caution Region with Urgent 1 obstacle present during VA configuration flights. Given the differences in routes, a heat map was produced to visually depict overlap in common routes. A comparison of VA to BL performance, using the heat map on the right, showed that time spent within the Caution Region with Urgent 1 obstacle present when flying the VA configuration was greater than BL on only three of the six routes they had in common. The middle graph shows that Route 7 was significantly more difficult than any other route.

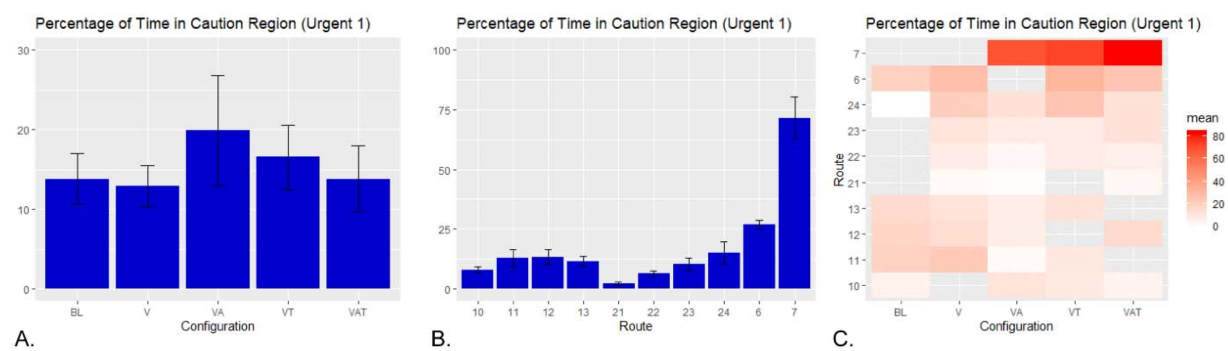


Figure 29. A: Approach Time Spent within the Caution Region with Urgent 1 obstacle present by Configuration. B: Approach Time Spent within the Caution Region with Urgent 1 obstacle present by Route. C: Approach Heat Map of Percentage Time Spent within the Caution Region with Urgent 1 obstacle present by Route and Configuration.

Results of the linear mixed effects models found configuration did not have a statistically significant effect on the percentage of time spent within the Caution Region with Urgent 1 obstacle present, $\chi2$ (4) = 8.07, $p = 0.09$. The percentages of time spent within the Caution Region with Urgent 1 obstacle present were statistically equivalent for all configurations during the approach phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the approach phase.

One Obstacle Present – Comparison of Baseline, Visual, and Audio.

The percentages of time spent within the Caution Region with Urgent 1 obstacle present were statistically equivalent compared to the Baseline cueing category in each the V+VT cueing category, $F(1, 27) = 1.69$, $p = 0.205$, the V+VAT cueing category, $F(1, 34) = 0.19$, p = 0.666, and the V+VT cueing category and in the VA+VAT cueing category, $F(1, 64) = 1.64$, $p = 0.205$. See Table 17 below for descriptive statistics.

Table 17. Percentages— Time in Caution Region with One Obstacle Present during Approach

Cueing Category	Mean	SE
BL	13.82	3.18
V+VT	14.70	2.36
VA+VAT	16.80	3.96

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 30).

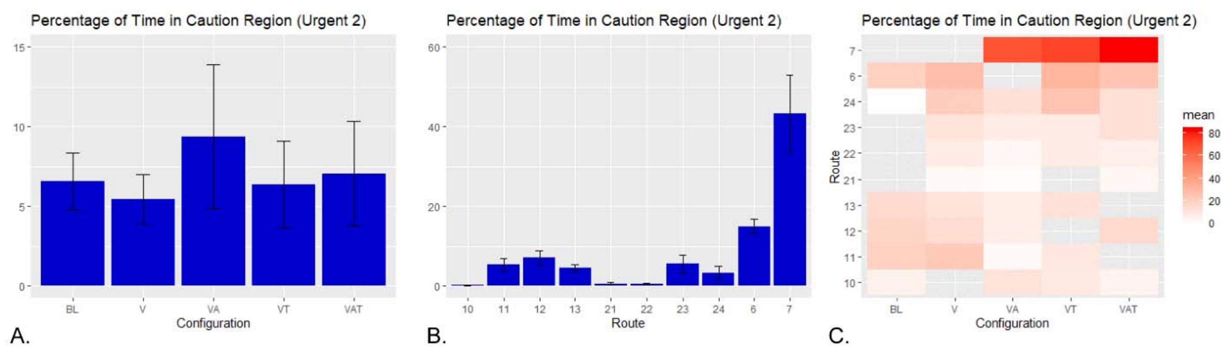


Figure 30. A: Approach Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Configuration. B: Approach Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Route. C: Approach Heat Map of Percentage Time Spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present by Route and Configuration.

Results of the linear mixed effects models found configuration did not have a statistically significant effect on the percentage of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present, $\chi2$ (4) = 9.17, p = 0.06. The percentages of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present were statistically equivalent for all configurations during the approach phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the approach phase.

Two Obstacles Present – Comparison of Baseline, Visual, and Audio.

The percentages of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present are statistically equivalent compared to the BL cueing category in each the V+VT cueing category, $F(1, 28) = 0.01$, $p = 0.942$, the V+VAT cueing category, $F(1, 34) = 0.23$, $p = 0.636$, and the V+VT cueing category and in the VA+VAT cueing category, $F(1, 64) = 0.51$, $p = 0.479$. See Table 18 below for descriptive statistics.

Table 18. Percentages— Time in Caution Region with Two Obstacles Present during Approach

Cueing Category	Mean	SE
BL	6.57	1.78
V+VT	5.90	1.55
VA+VAT	8.17	2.74

Percentage of Time within the Warning/Rotor Region during Approach.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 obstacle present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 31).

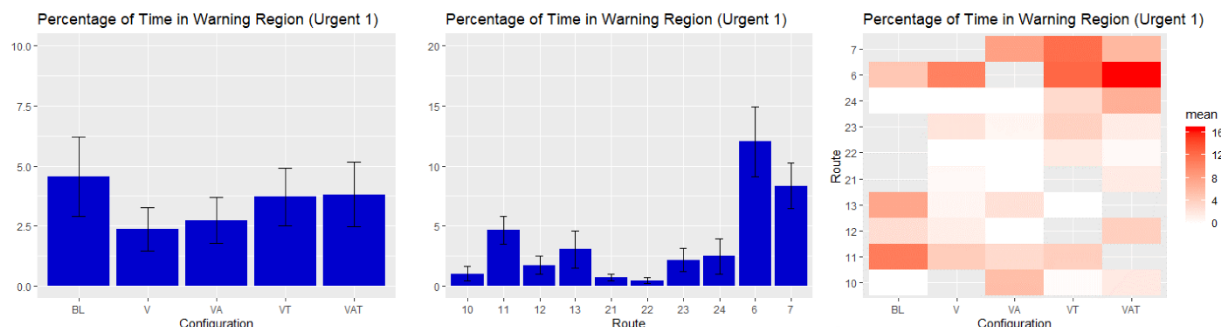


Figure 31. A: Approach Time Spent within Warning/Rotor Region with Urgent 1 obstacle present by Configuration. B: Approach Time Spent within Warning/Rotor Region with Urgent 1 obstacle present by Route. C: Approach Heat Map of Percentage Time Spent within Warning/Rotor Region with Urgent 1 obstacle present by Route and Configuration.

Results of the linear mixed effects models found configuration had a statistically significant effect on the percentage of time spent within the Warning/Rotor Region, χ^2 (4) = 11.35, $p < 0.05$. A post hoc analysis of the various configurations revealed no difference in the percentages of time spent within the Warning/Rotor Region with Urgent 1 obstacle present compared to the BL configuration and each, the V configuration, t (9.69) = 1.677, $p > 0.05$, the VA configuration, t (9.99) = 2.206, $p > 0.05$, and the VT configuration, t (10.66) = 0.906, $p > 0.05$. However, the percentage of time within the Warning/Rotor Region with Urgent 1 obstacle present was significantly higher in VAT configuration than in BL configuration, t (16) = 2.145, $p < 0.05$.

One Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

The percentages of time spent within the Warning/Rotor Region with Urgent 1 obstacle present were statistically equivalent in each of the following comparisons: the V and VT configurations, $F(1, 22) = 0.79$, $p = 0.383$, the V and VA configurations, $F(1, 18) = 1.61$, $p = 0.220$, and the VT and VAT configurations, $F(1, 22) = 0.03$, $p = 0.868$. However, the percentage of time spent within the Warning/Rotor Region with Urgent 1 obstacle present was higher in the VAT configuration than in the VT configuration, $F(1, 21) = 4.86$, $p = 0.039$. See Table 19 below for descriptive statistics.

Table 19. Percentages— Time in Warning/Rotor Region with One Obstacle Present during Approach.

Cueing Category	Mean	SE
V	2.37	0.90
VT	3.71	1.20
VA	2.74	0.96
VAT	3.80	1.34

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 32).

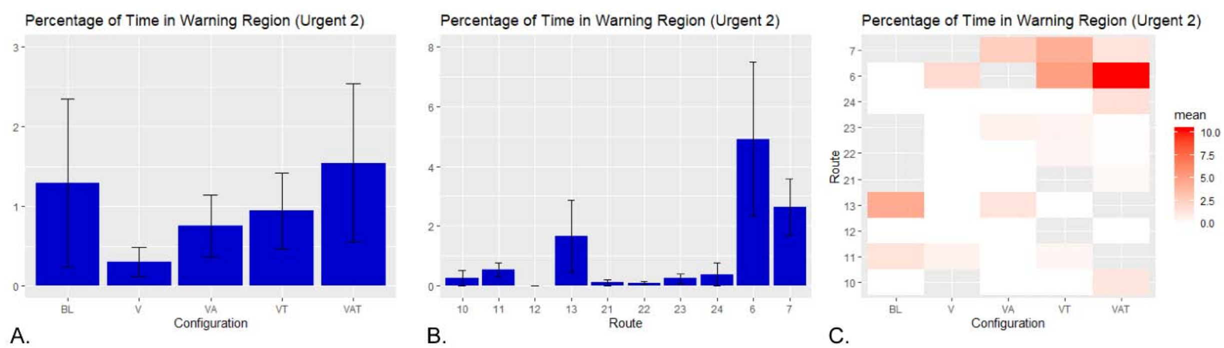


Figure 32. A: Approach Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Configuration. B: Approach Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Route. C: Approach Heat Map of Percentage Time Spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present by Route and Configuration.

In 57 of the 83 flights during the approach phase, 68.7% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent in within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all configurations during the approach phase, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the approach phase.

Two Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

In 69% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the approach phase. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the approach phase were equivalent for all configurations. See Table 20 below for descriptive statistics.

Table 20. Percentages— Time in Warning/Rotor Region with One Obstacle Present during Approach.

Cueing Category	Mean	SE
V	0.30	0.19
VT	0.94	0.48
VA	0.75	0.39
VAT	1.54	0.99

Landing Performance Data

Percentage of Time within Caution Region during Landing.

One Obstacle Present – Comparison of Baseline, Visual, and Audio.

In 66.7% of flights, the helicopter never entered the Caution Region with Urgent 1 obstacle present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that cueing category had a significant effect. The percentages of time spent within the Caution Region with Urgent 1 obstacle present were equivalent for all three cueing categories. See Table 21 below for descriptive statistics.

Table 21. Percentages— Time in Caution Region with One Obstacle Present during Landing

Cueing Category	Mean	SE
BL	33.33	21.08
V+VT	29.19	6.76
VA+VAT	21.98	6.85

Two Obstacles Present – Comparison of Baseline, Visual, and Audio.

In 88.5% of flights, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that cueing category had a significant effect. The percentages of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all three cueing categories. See Table 22 below for descriptive statistics.

Table 22. Percentages— Time in Caution Region with Two Obstacles Present during Landing

Cueing Category	Mean	SE
BL	1.67	1.67
V+VT	2.16	1.36
VA+VAT	5.25	3.43

Percentage of Time within Warning/Rotor Region during Landing.

One Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

In 82% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 obstacle present during the landing phase. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 obstacle present during the landing phase were equivalent for all configurations. See Table 23 below.

Table 23. Percentages— Time in Warning/Rotor Region with One Obstacle Present during Approach.

Cueing Category	Mean	SE
V	12.63	7.17
VT	20.16	7.45
VA	0	0
VAT	12.36	6.82

Two Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

Given that in 90% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the landing phase, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present during the landing phase were equivalent for all configurations (Table 24).

Table 24. Percentages— Warning/Rotor Region with Two Obstacles during Landing

Cueing Category	Mean	SE
V	12.15	6.85
VT	12.77	6.84
VA	0	0
VAT	5.39	5.39

Deviations during Landing.

Figure 33 shows the Deviation at Touchdown as a function of configuration. 25% of the landings had a Deviation at TouchDown less than 10’, 50% of the landings had a Deviation at TouchDown less than 20’ and 75% of the landings had a Deviation at TouchDown less than 28’.

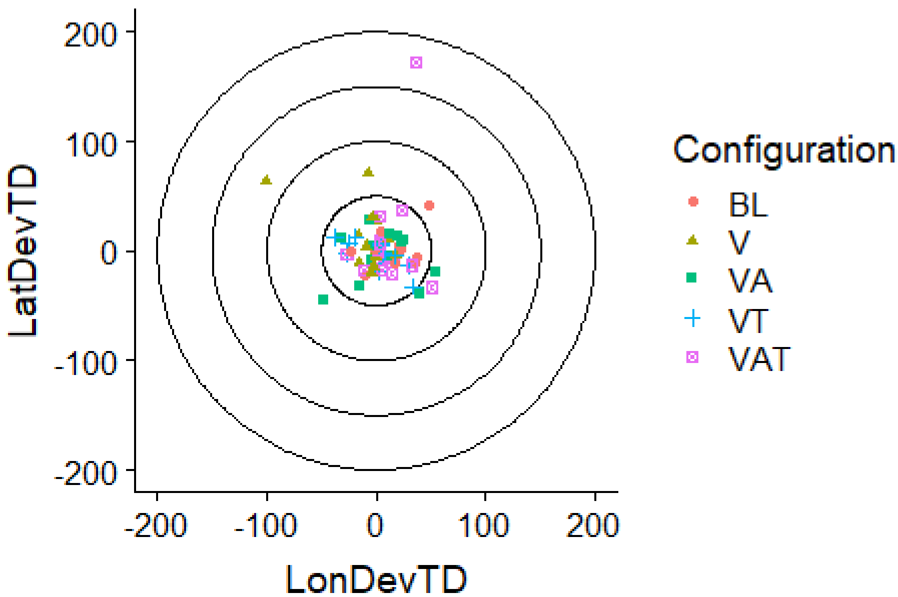


Figure 33. Deviations at Touchdown.

The average Deviations at TouchDown during the landing phase were calculated as a function of the Configuration, the Route of Flight, and a combination of Configuration x Route of Flight. Although configuration was the main factor of interest in this study, the route of flight was a confounding variable and a greater contributor to the overall variation in Deviation at TouchDown during landing. Any comparison across configurations must take into account the route of flight.

Deviations at touchdown were first plotted to visually inspect distribution of time across each of the configurations (see Figure 34). Visual examination of the graph on the left suggests that the Deviation at TouchDown was the highest during VA configuration flights. A comparison of VA to BL performance, using the heat map on the right, shows VA performance was higher than BL on only two of the six routes they had in common.

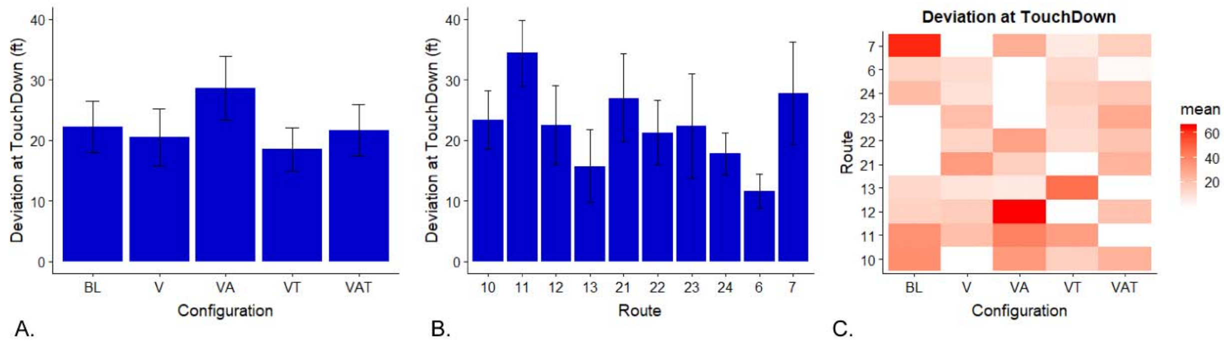


Figure 34. A: Landing Deviations at Touchdown by Configuration. B: Landing Deviations at Touchdown by Route. C: Landing Heat Map of Deviations at Touchdown by Route and Configuration.

In order to compare performance in the BL configuration to each of the other four configurations, linear mixed effects models were developed with and without configuration as a regressor. Configuration and route of flight were considered fixed effects and subject intercept was a random effect. Likelihood ratio tests were run to contrast the full model with the configuration effect to the partial model without the configuration effect.

Configuration did not have a statistically significant effect on Deviations at Touchdown, $\chi^2 = 4.88$, $p = 0.33$. The Deviations at TouchDown are statistically equivalent for all configurations, suggesting cueing configuration did not significantly impact proximity of the aircraft to obstacles during the landing phase.

All Phases Combined (Except Landing).

In all, there were 432 flight segments, distributed as follows: 89 Taxi, 89 Takeoff, 89 En-route, 83 Approach, and 82 Landing. The landing data were removed prior to conducting the following analysis.

Percentage of Time Helicopter was in the Caution Region.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The percentage of time the helicopter spent within the Caution Region with Urgent 1 obstacle present during all flight phases was calculated as a function of the Configuration, the Route of Flight, and a combination of Configuration x Route of Flight. Although configuration was the main factor of interest in this study, the route of flight was a confounding variable and a greater contributor to the overall variation in the time spent within a threat level region during each phase. Any comparison across configurations must take into account the route of flight. In order to compare performance in the BL configuration to each of the other four configurations, where possible, linear mixed effects models were developed with and without configuration as a regressor. Configuration and route of flight were considered fixed effects and subject intercept was a random effect. Likelihood ratio tests were run to contrast the full model with the configuration effect to the partial model without the configuration effect.

The amount of time spent within the Caution Region with Urgent 1 obstacle present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 35).

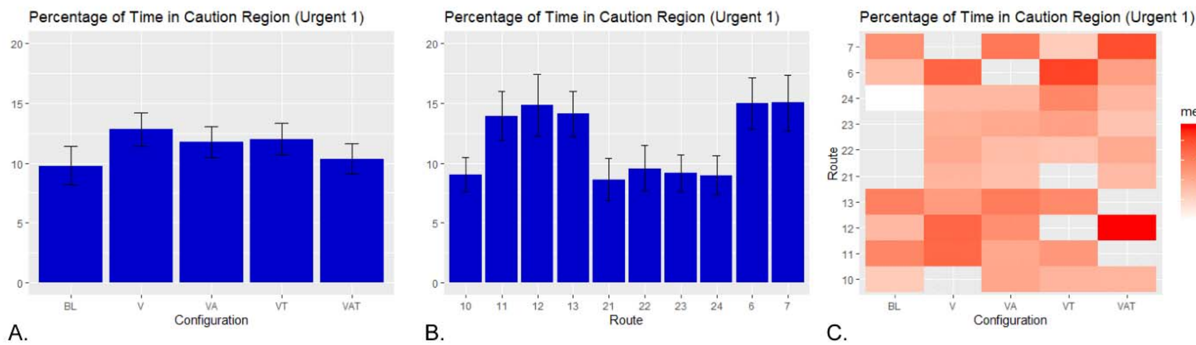


Figure 35. A: Percentage of time within the Caution Region with Urgent 1 obstacle present across phases by Configuration. B: Percentage of time within the Caution Region with Urgent 1 obstacle present across phases by Route. C: Percentage of time within the Caution Region with Urgent 1 obstacle present across phases by Route and Configuration.

Results of the linear mixed effects models found configuration did not have a statistically significant effect on the percentage of time spent within the Caution Region with Urgent 1 obstacle present, χ^2 (4) = 8.02, p = 0.09. The percentages of time spent within the Caution Region with Urgent 1 obstacle present were statistically equivalent for all configurations.

One Obstacle Present – Comparison of Baseline, Visual, and Audio.

Linear mixed effects models were developed to estimate the effects of cueing category, phase of flight, route of flight, and subjects. Cueing category, phase of flight, and route of flight were considered fixed effects variables and subject intercept was a random effect.

The percentage of time spent within the Caution Region with Urgent 1 obstacle present was slightly higher compared to the BL cueing category in each the V+VT cueing category, F(1, 172) = 5.84, p = 0.017, and the VA+VAT cueing category, F(1, 177) = 4.19, p = 0.042. The percentages of time spent within the Caution Region with Urgent 1 obstacle present were statistically equivalent in the V+VT cueing category and in the VA+VAT cueing category, F(1, 292) = 0.58, p = 0.448. See Table 25 below for descriptive statistics.

Table 25. Percentages— Time in Caution Region with One Obstacle Present across All Phases

Cueing Category	Mean	SE
BL	9.77	1.60
V+VT	12.41	0.96
VA+VAT	11.03	0.90

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 36).

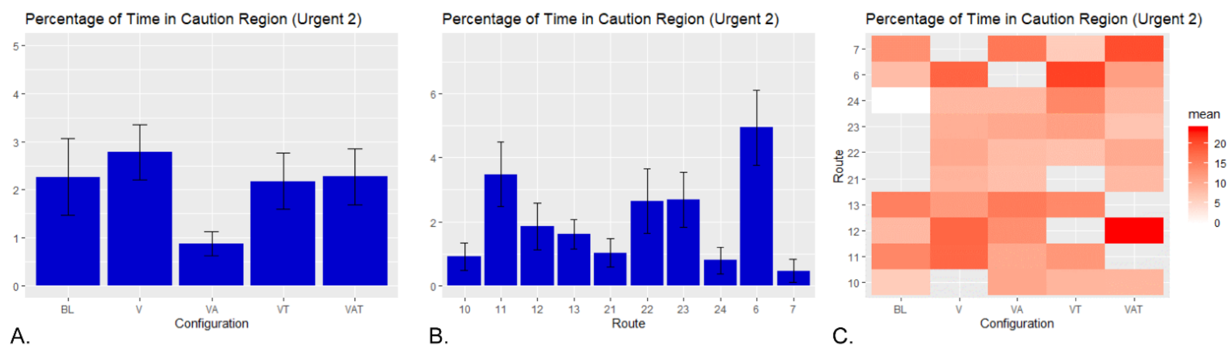


Figure 36. A: Percentage of time in the Caution Region with Urgent 1 and Urgent 2 obstacles present across phases by Configuration. B: Percentage of time in the Caution Region with Urgent 1 and Urgent 2 obstacles present across phases by Route. C: Percentage of time in the Caution Region with Urgent 1 and Urgent 2 obstacles present across phases by Route and Configuration.

In 67.4% of the flight segments, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flight segments made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within an the Caution Region with Urgent 1 and Urgent 2 obstacles present caution region were equivalent for all configurations.

Two Obstacles Present – Comparison of Baseline, Visual, and Audio.

In 67.4% of flights, the helicopter never entered the Caution Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that cueing category had a significant effect. The percentages of time spent within the Caution Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all three cueing categories. See Table 26 below for descriptive statistics.

Table 26. Percentages— Time in Caution Region with Two Obstacles Present across All Phases

Cueing Category	Mean	SE
BL	2.27	0.81
V+VT	2.48	0.41
VA+VAT	1.59	0.32

Percentage of Time Helicopter was within the Warning/Rotor Region across All Phases of Flight.

One Obstacle Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 obstacle present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 37).

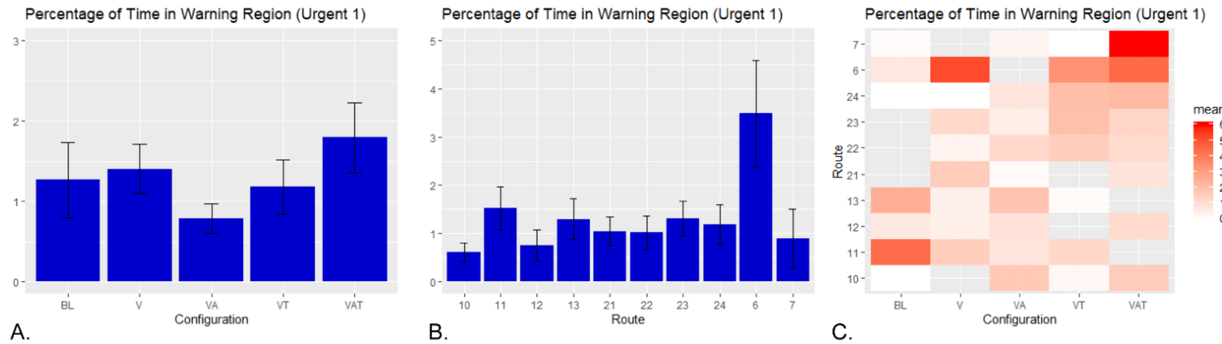


Figure 37. A: Percentage of time within the Warning/Rotor Region with Urgent 1 obstacle present across phases by Configuration. B: Percentage of time within the Warning/Rotor Region with Urgent 1 obstacle present across phases by Route. C: Percentage of time within the Warning\/Rotor Region with Urgent 1 obstacle present across phases by Route and Configuration.

In 58.7% of the flight segments, the helicopter never entered the Warning/Rotor Region with Urgent 1 obstacle present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 obstacle present were equivalent for all configurations.

One Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

The percentages of time spent within the Warning/Rotor Region with Urgent 1 obstacle present were statistically equivalent in the following comparisons: V and VT configurations, $F(1, 132) = 0.34$, $p = 0.558$; V and VA configurations, $F(1, 137) = 0.01$, p = 0.983; and VT and VAT configurations, $F(1, 137) = 1.69$, $p = 0.195$. The percentage of time spent within the Warning/Rotor Region with Urgent 1 obstacle present was higher in the VAT configuration than in the VA configuration, $F(1, 137) = 4.55$, $p = 0.035$. See Table 27 below for descriptive statistics.

Table 27. Percentages— Time in Warning/Rotor Region with One Obstacle Present across All Phases

Cueing Category	Mean	SE
V	1.40	0.30
VT	1.18	0.34
VA	0.79	0.18
VAT	1.79	0.43

Two Obstacles Present – Cueing Configurations Compared to Baseline.

The amount of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present was first plotted to visually inspect distribution of time across each of the configurations (see Figure 38).

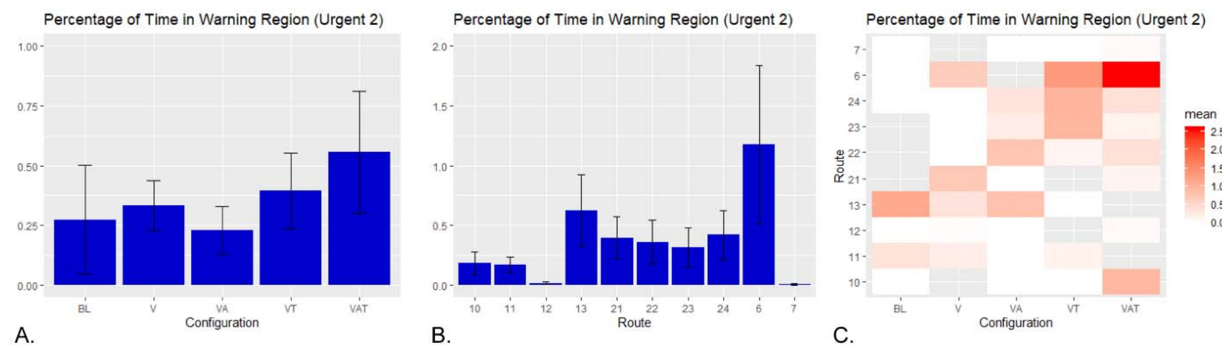


Figure 38. A: Percentage of time within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present across phases by Configuration. B: Percentage of time within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present across phases by Route. C: Percentage of time within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present across phases by Route and Configuration.

In 82.3% of the flight segments, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present. The high number of "zero" data flights made it impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all configurations.

Two Obstacles Present – Comparison of Visual, Visual-Tactile, Visual-Audio, and Visual-Audio-Tactile.

Give that in 82.3% of flights, the helicopter never entered the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present, it was impossible to find a suitable statistical test for this data. However, an examination of the means and standard errors provided no evidence that configuration had a significant effect. The percentages of time spent within the Warning/Rotor Region with Urgent 1 and Urgent 2 obstacles present were equivalent for all configurations. See Table 28 below for descriptive statistics.

Table 28. Percentages— Time in Warning/Rotor Region with Two Obstacles Present across All Phases

Cueing Category	Mean	SE
V	0.33	0.10
VT	0.39	0.16
VA	0.23	0.10
VAT	0.55	0.25

Summary of Crashes.

The crash metrics did not have enough flights with non-zero values to build regression models. The frequencies of crash metrics for each phase of flight are in Table 29 below.

Table 29. Frequencies— Crashes across Each Phase of Flight

Type	Taxi	Takeoff	En-Route	Approach	Landing
Total Flights	80	80	80	76	75
Soft	0	0	3	1	0
Hard	0	1	10	9	6

Subjective Measures

Training Effectiveness Ratings.

Pilot responses for each of the seven training effectiveness questions were aggregated and grouped into positive, neutral and/or negative percentages and are presented in Figure 39. The pilots' responses were positive for all training elements to include helpfulness of classroom and simulator training, training materials, training length, and preparation the training provided for flying missions in the simulator. Average of ratings were 4.27 or higher on a 5-point scale. Comments for the training questionnaire are listed in Appendix D.

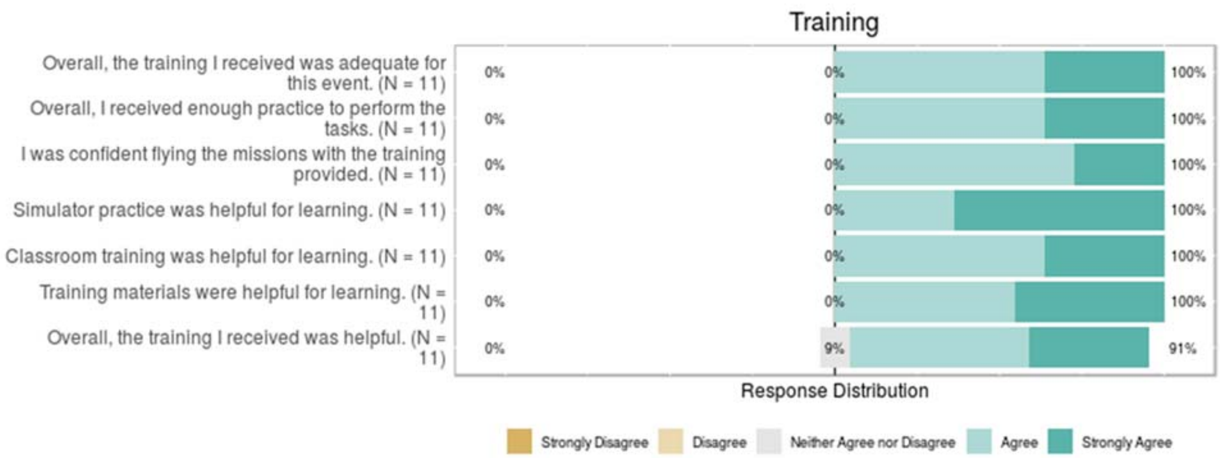


Figure 39. Training effectiveness questionnaire ratings.

Bedford Workload Ratings.

Workload rating response distributions were computed for each experimental condition. Ratings of 1-3, 4-6, 7-9, and 10 were grouped to represent categorical levels of workload: "low", "moderate", "high", and "impossible". The majority of workload ratings were in the "low" to "moderate" categories as seen in Figure 40 below. The Visual + Audio condition had the lowest average workload with a mean of 3.65 on a 10 point scale. The Baseline condition had more "high" workload ratings than any other condition and also the highest average workload rating with a mean of 5.30 on a 10 point scale. Pilot comments are contained in Appendix D.

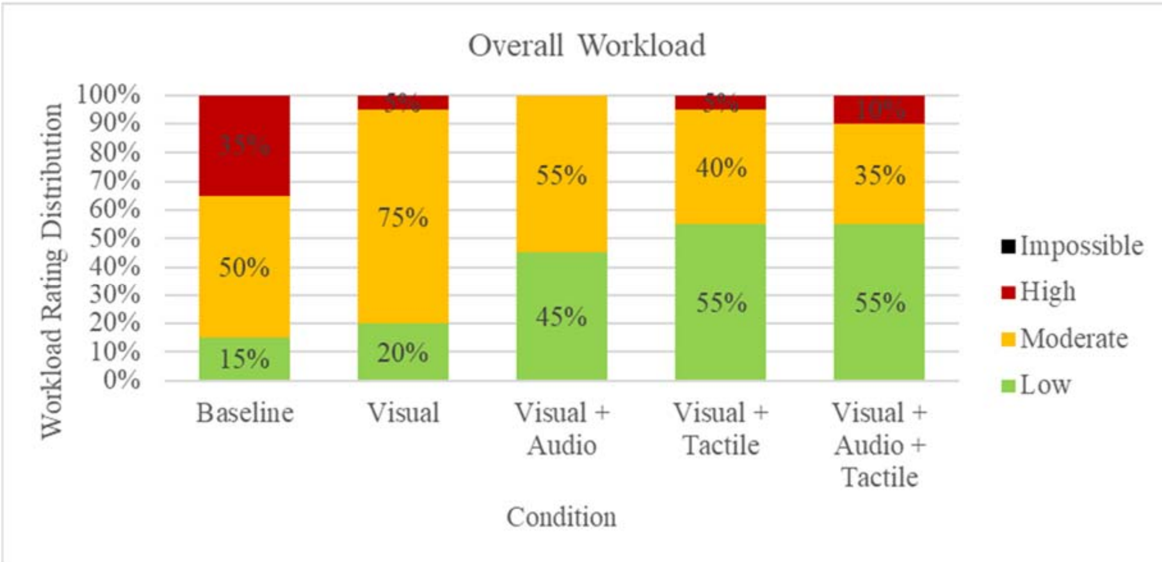


Figure 40. Overall Workload questionnaire ratings.

Wilcoxon signed rank test (WRST) was used to compare pilot workload ratings by condition (Table 5). Workload ratings were significantly higher (worse) for the Baseline condition than for every condition in which cueing was provided. There were no significant differences in workload ratings between the cueing conditions.

Table 30. Wilcoxon Signed-Ranks Test Table for Overall Workload

	Baseline	Visual	Visual+ Audio	Visual + Tactile	Visual + Audio + Tactile
Baseline					
Visual	*Z* = -2.446 *p* = 0.01428				
Visual + Audio	*Z* = -3.0703 *p* = 0.00214	*Z* = -1.4483 *p* = 0.14706			
Visual + Tactile	*Z* = -2.7219 *p* = 0.00652	*Z* = -1.0651 *p* = 0.28462	*Z* = -0.5022 *p* = 0.61708		
Visual + Audio + Tactile	*Z*= -2.5337 *p* = 0.0114	*Z* = -1.2152 *p* = 0.22246	*Z* = -0.4654 *p* = 0.63836	*Z* = -0.284 *p* = 0.77948	

Note. Results are color coded green for significance (p<.05) and red for no significance.

Workload rating response distributions were further computed for each experimental condition when pilots used the PMD (Figure 41). Ratings of 1-3, 4-6, 7-9, and 10 were grouped to represent categorical levels of workload: “low”, “moderate”, “high”, and “impossible”, respectively. All ratings were within the low to moderate workload categories for those conditions in which cueing was provided while using the PMD. Half of the ratings for the baseline condition (no cueing) were in the high workload category.

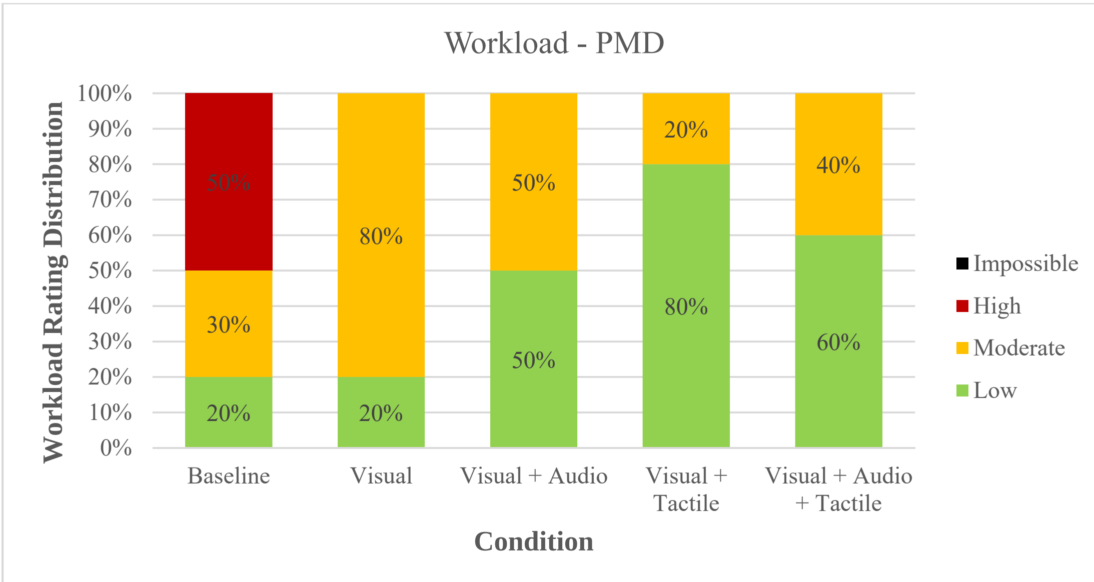


Figure 41. Bedford Workload questionnaire ratings using PMD.

Workload rating response distributions were also computed for each experimental condition when pilots used the HMD (Figure 42). Ratings of 1-3, 4-6, 7-9, and 10 were grouped to represent categorical levels of workload: “low”, “moderate”, “high”, and “impossible”, respectively. Ratings were mostly in the low to moderate workload category for all conditions while using the HMD.

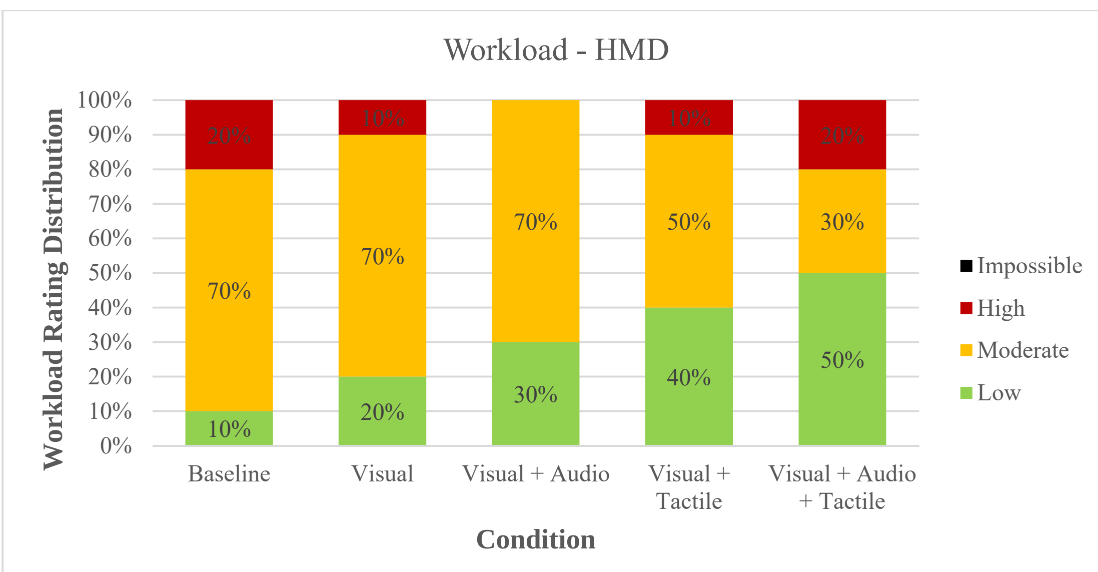


Figure 42. Bedford Workload questionnaire ratings using HMD.

WSRT values were computed for workload by display type (HMD vs PMD) for the cueing conditions. Workload ratings across all conditions in which cueing was provided were significantly lower using the PMD (M=3.625) rather than the HMD (M=4.275), Z = -2.0218 p = 0.043.

Situation Awareness Ratings.

Situation awareness rating response distributions were computed for each experimental condition. Ratings of 1-3, 4-6, 7-9, and 10 were grouped to represent categorical levels of SA: high, moderate, low, and none as seen in Figure 43 below. Nearly all ratings for SA were in the moderate to high categories for all conditions in which cueing was provided. The Visual + Audio + Tactile condition had the highest average SA rating with a mean of 3.19 on a 10-point scale, with 1 being the highest SA and 10 being no SA. The Baseline condition scored the lowest with a mean of 5.80 on a 10-point scale. Pilot comments are contained in Appendix D.

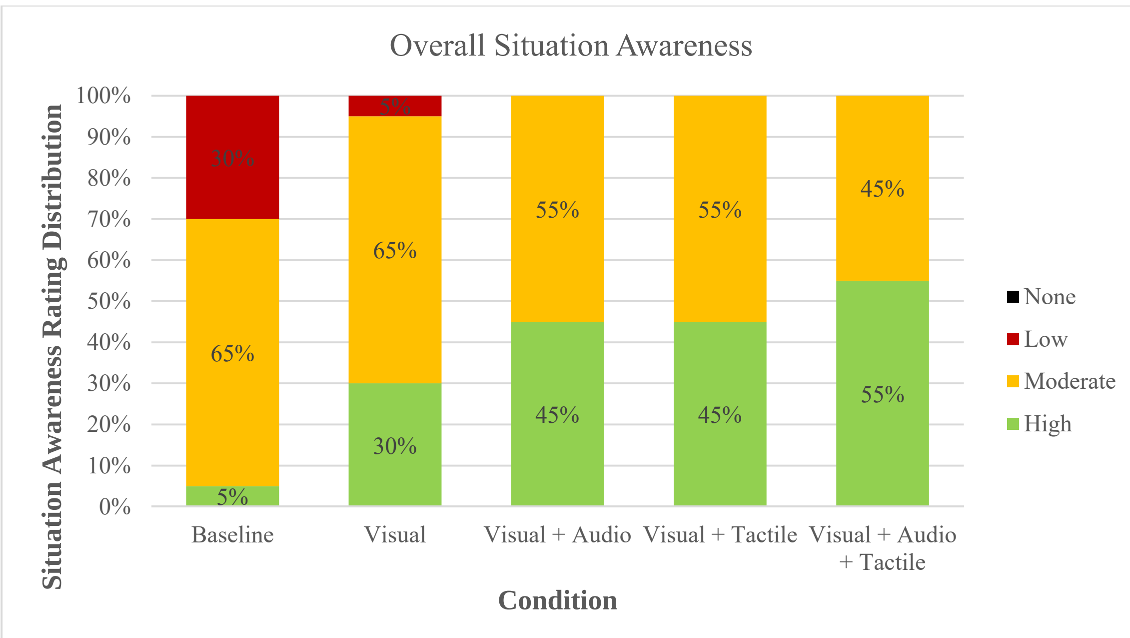


Figure 43. Overall Situation Awareness questionnaire ratings.

WSRT values were computed for situation awareness ratings by condition. Results are summarized in Table 31. Situation awareness ratings were significantly lower (worse) for the baseline condition than every other condition in which cueing was provided. There were no significant differences in situation awareness ratings between the cueing conditions in which one or more cueing modalities were provided.

Table 31. Wilcoxon Signed-Ranks Test Table for Situation Awareness.

	Baseline	Visual	Visual+ Audio	Visual + Tactile	Visual + Audio + Tactile
Baseline					
Visual	*Z* = -2.7664 *p* = 0.0056				
Visual + Audio	*Z* = -3.6822 *p* = 0.0002	*Z* = -1.3065 *p* = 0.1902			
Visual + Tactile	*Z* = -3.3847 *p* = 0.0007	*Z* = -0.8047 *p* = 0.42372	*Z* = -0.5883 *p* = 0.5552		
Visual + Audio + Tactile	*Z* = -3.5816 *p* =0 .0003	*Z* = -1.7891 *p* = 0.07346	*Z* = -0.9308 *p* = 0.35238	*Z* = -1.2545 *p* = 0.2113	

Note. Results are color coded green for significance ($p < .05$) and red for no significance

Situation awareness rating response distributions were also computed for each experimental condition when pilots used the PMD (Figure 44). Ratings of 1-3, 4-6, 7-9, and 10 were grouped to represent categorical levels of SA: high, moderate, low, and none, respectively. All ratings for SA while using the PMD were in moderate to high categories for all conditions in which cueing was provided. Forty percent of the ratings for the PMD in the baseline condition were in the low SA category.

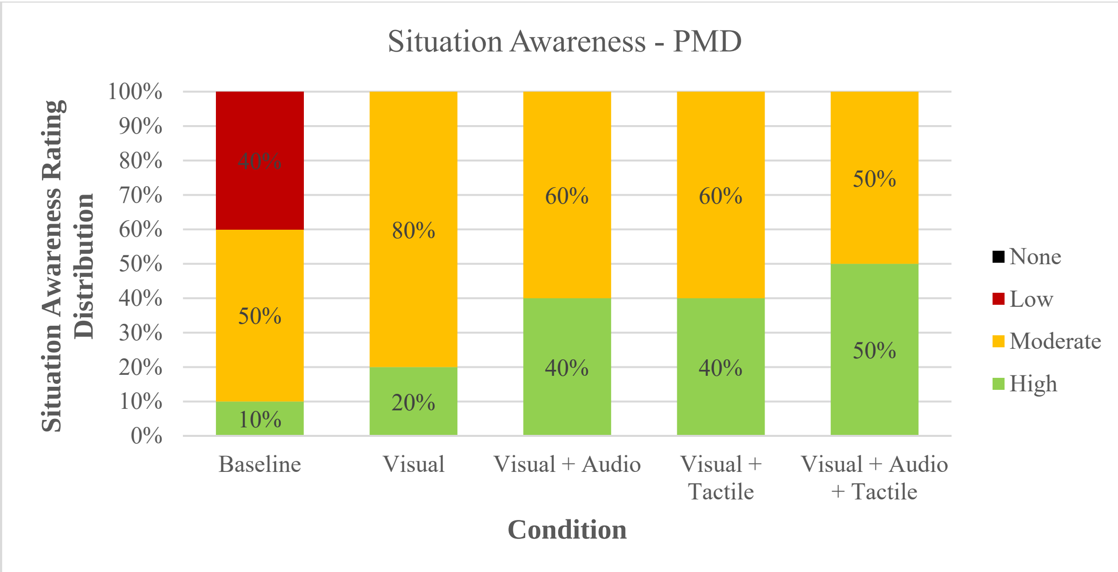


Figure 44. Situation Awareness questionnaire ratings using PMD.

Situation awareness rating response distributions were computed for each experimental condition when pilots used the HMD (Figure 45). Ratings of 1-3, 4-6, 7-9, and 10 were grouped to represent categorical levels of SA: high, moderate, low, and none, respectively. Nearly all ratings for SA while using the HMD were in the moderate to high categories for all conditions in which cueing was provided. Pilots reported their SA was lowest when conducting missions when no cueing was provided to them (baseline).

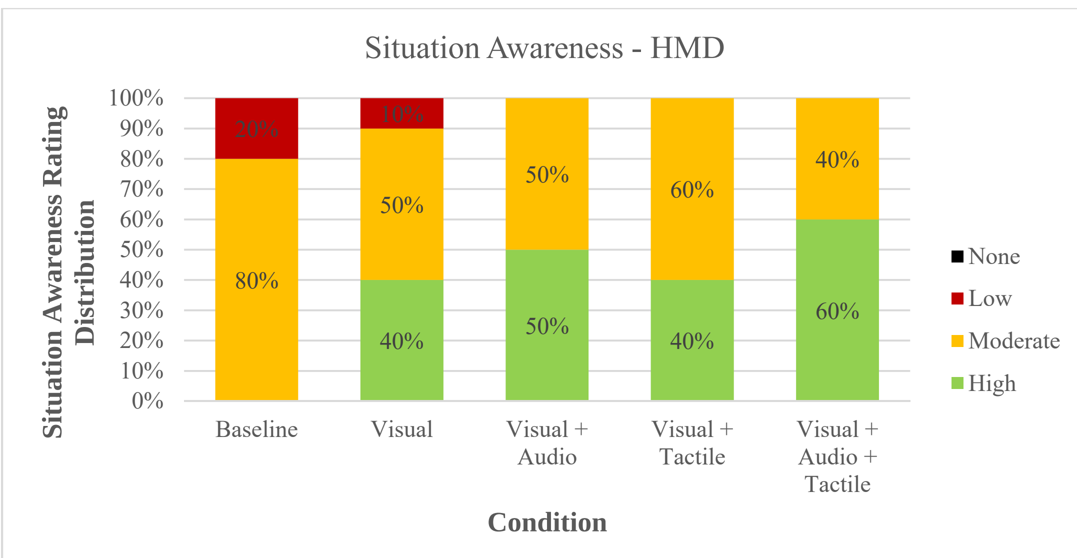


Figure 45. Situation Awareness questionnaire ratings using HMD.

WSRT values were computed for situation awareness by display type. Situation awareness ratings across all conditions in which cueing was provided were not statistically significant between the PMD (M=3.675) and the HMD (M=3.675), Z = -0.0715, p = 0.944.

Visual Cueing Usability Ratings.

Visual cueing usability ratings were calculated for each the Integrated Collision Avoidance Display (ICAD) and the Collision Avoidance Symbology (ICE Screen). The ICAD was displayed on the inboard MFD and the Collision Avoidance Symbology (ICE Screen) was displayed using a perspective view either on the outboard MFD or through the HMD. Overall, the visual cueing usability ratings were fair to good with the average rating of 3.4 out of 5.0. The highest ratings were a 4.0 out of 5.0 for intuitiveness. The visual cueing usability ratings are presented below in Figures 46 and 47.

Integrated Collision Avoidance Display (ICAD).

The responses for each of the seventeen usability questions on the ICAD were aggregated and grouped into positive, neutral and negative percentages for each question and are presented in Figure 46 below. Comments are listed in Appendix D.

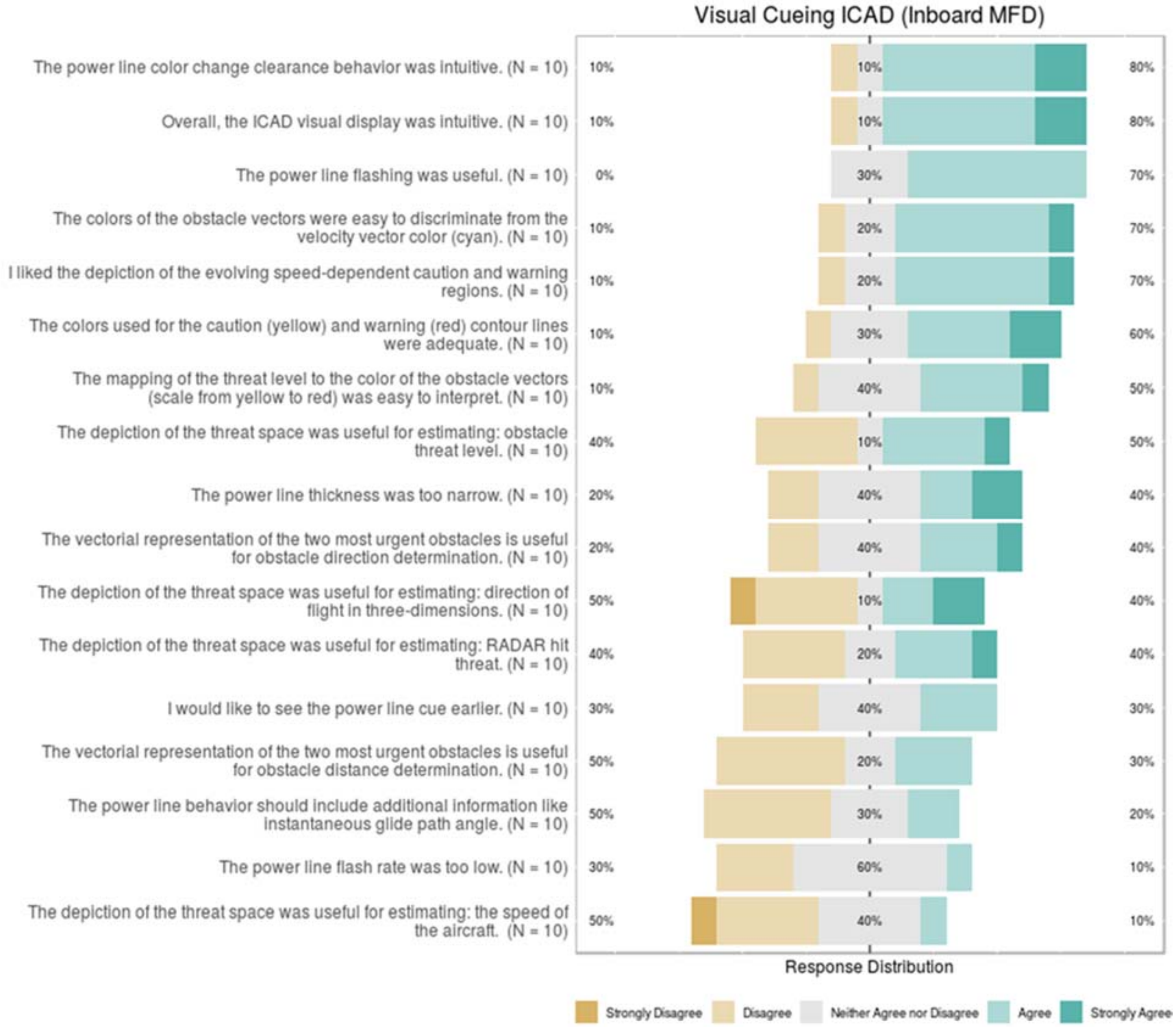


Figure 46. Integrated Collision Avoidance Display (ICAD) usability ratings.

Collision Avoidance Symbology (ICE Screen).

The responses for each of the seven usability questions on the Collision Avoidance Symbology (ICE Screen) were aggregated and grouped into positive, neutral and negative percentages for each question and are presented in Figure 47 below. The majority of questionnaire responses were positive with either "agree" or "strongly agree" responses. Comments are listed in Appendix D.

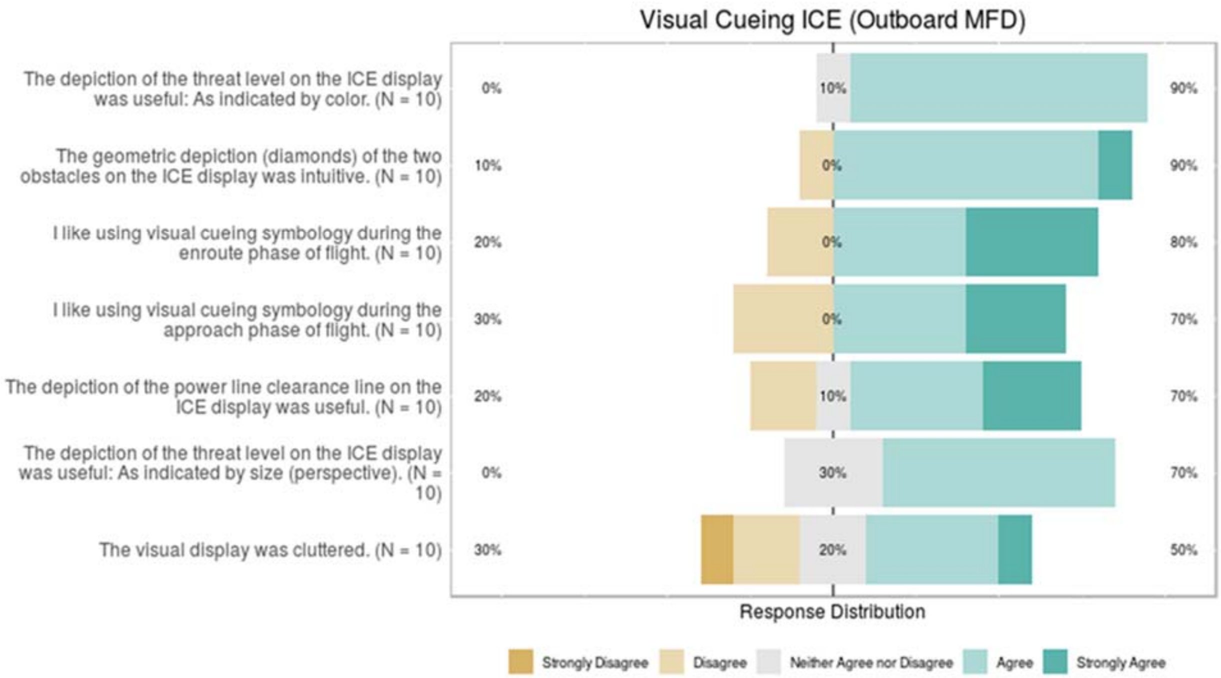


Figure 47. Collision Avoidance Symbology (ICE Screen) usability ratings.

Spatial Auditory Cueing Usability Ratings.

The responses for each of the twenty-nine usability questions on the Augmented-Reality Spatial Auditory Display (ARSAD) cueing were aggregated and grouped into positive, neutral and negative percentages for each question and are presented in Figure 48 below. The majority of questionnaire responses were positive with either "agree" or "strongly agree" responses for ARSAD usability. Comments are listed in Appendix D.

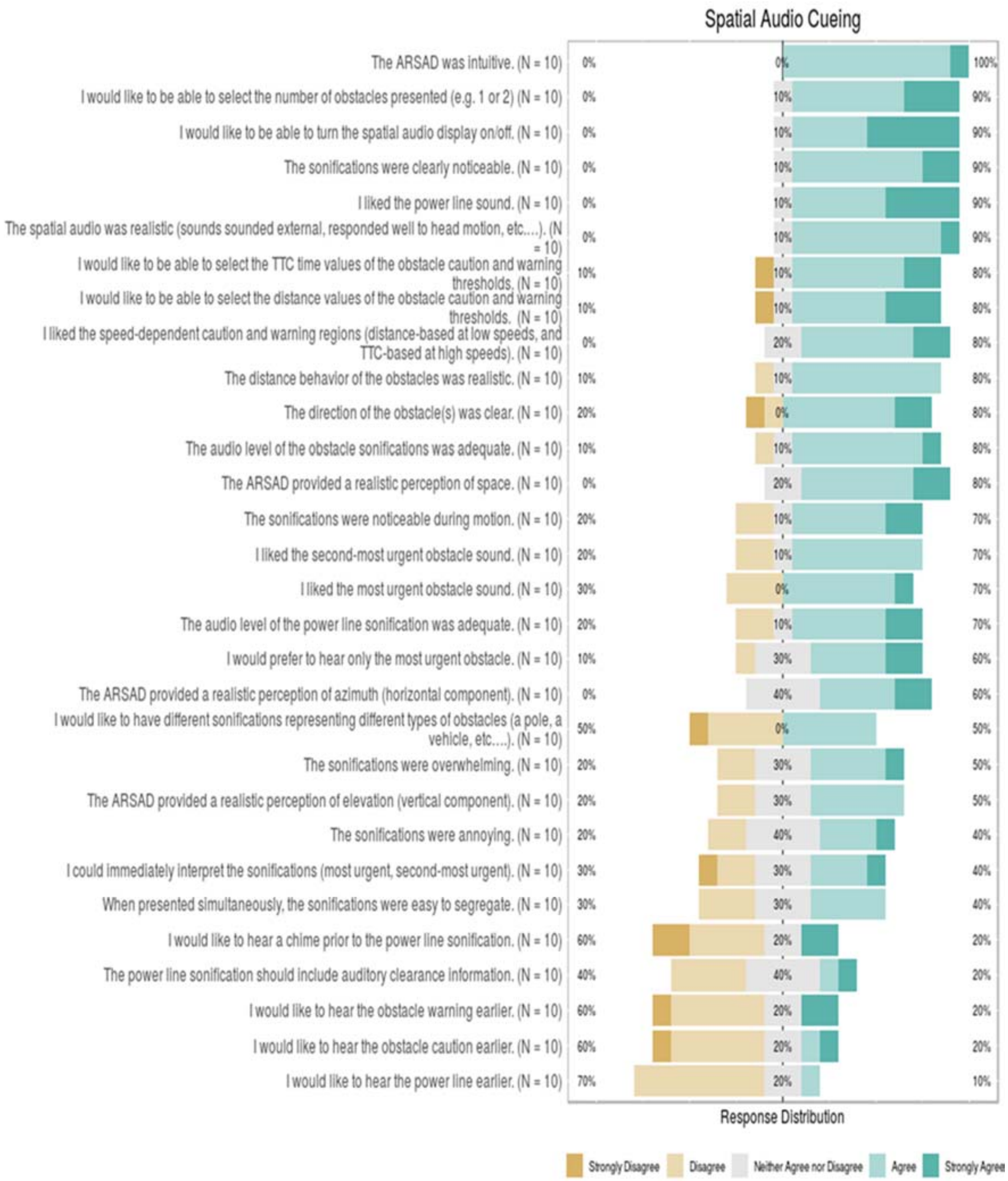


Figure 48. Augmented-Reality Spatial Auditory Display (ARSAD) usability ratings.

Tactile Cueing Usability Ratings.

The responses for each of the fifteen usability questions for tactile cueing were aggregated and grouped into positive, neutral and negative percentages for each question and are presented in Figure 49 below. The majority of questionnaire responses provided by the pilots were positive about usability of tactile cueing during missions. Comments are listed in Appendix D.

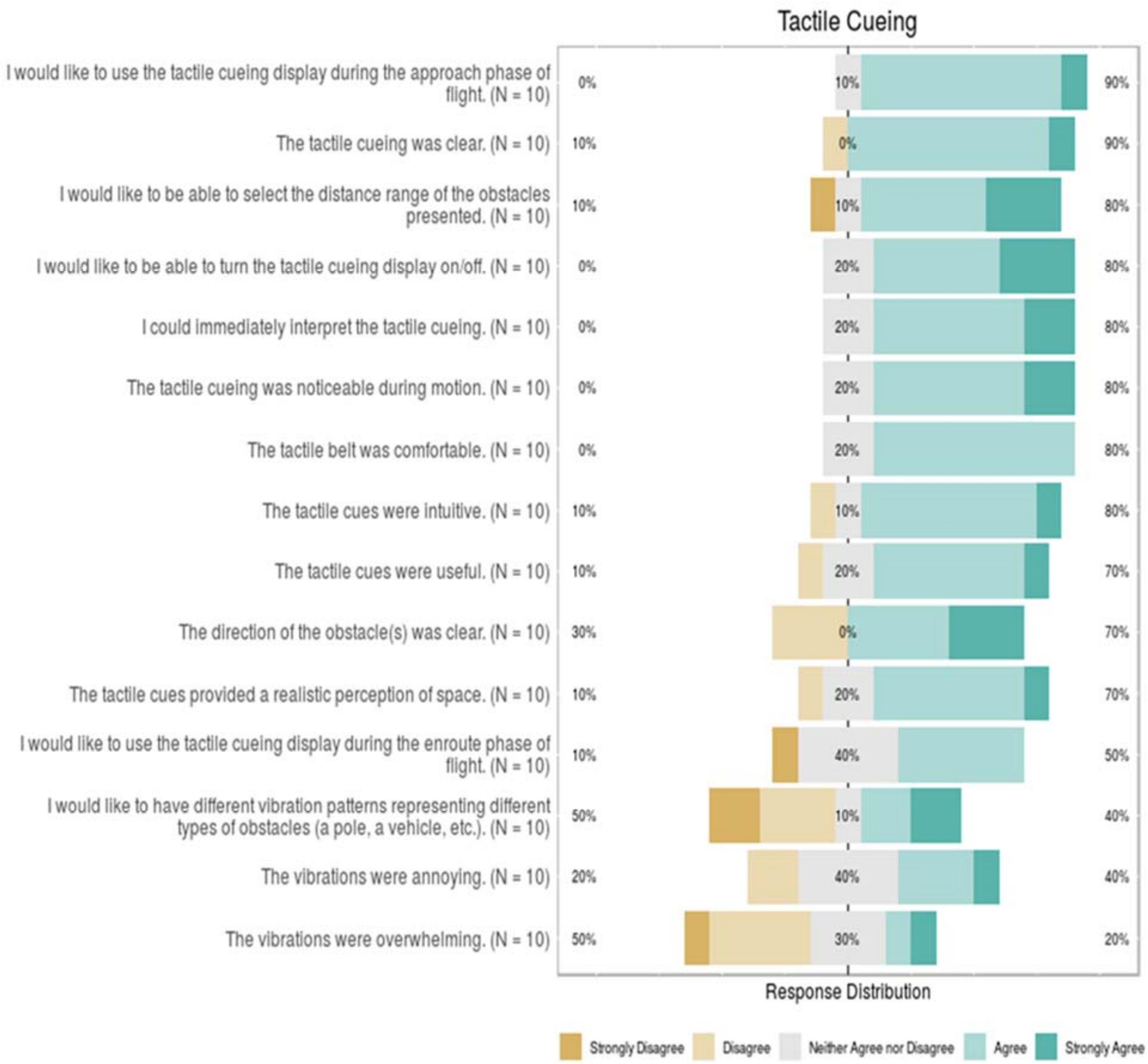


Figure 49. Tactile cueing usability ratings.

Overall Cueing Performance Ratings.

The responses for each of the twelve overall performance questions were aggregated and grouped into positive, neutral and negative percentages for each question and are presented in Figure 50. The majority of questionnaire responses were positive with regard to the impact of cueing on pilot performance. Comments are listed in Appendix D.

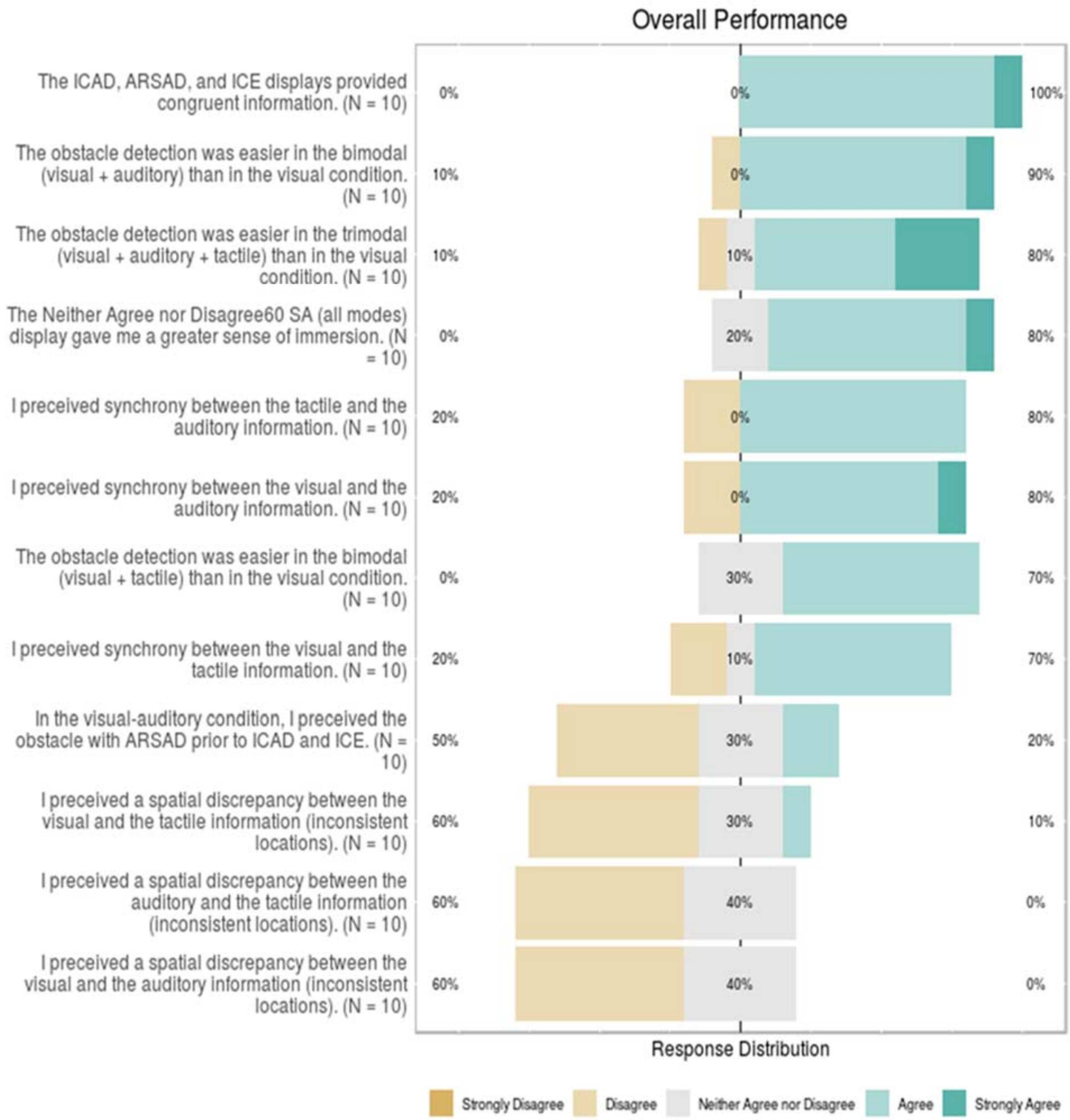


Figure 50. Overall Cueing Performance Ratings.

Pilot Preferences for Cueing Conditions.

Preferences for each condition were collected and ranked from 1 to 5 with 1 being the most preferred combination of cueing to 5 being the least preferred combination of cueing. The condition with visual and audio cueing was ranked highest while the baseline condition, which contained no cueing, was ranked lowest.

Ranked Preferences.

1 Visual + Audio

2 Visual + Audio + Tactile

3 Visual + Tactile (tied with 4)

4 Visual (tied with 3)

5 Baseline

Additionally, 70% of the pilots preferred the panel mounted display (PMD) over the HMD with 30%.

Trust in Automation Ratings.

Trust in automation ratings were calculated for each cueing type: Visual, Auditory, and Tactile. The average overall trust in automation rating was 3.84 out of a possible 5.0. The trust in automation ratings are presented below in Figures 51, 52 and 53.

Trust in Automation – Visual Cueing.

The responses for each of the four trust in automation questions for the visual cueing were aggregated and grouped into positive, neutral and negative percentages for each question and are presented in Figure 51 below. The average trust in automation – visual cueing rating was 3.75 out of a possible 5.0. Comments are listed in Appendix D.

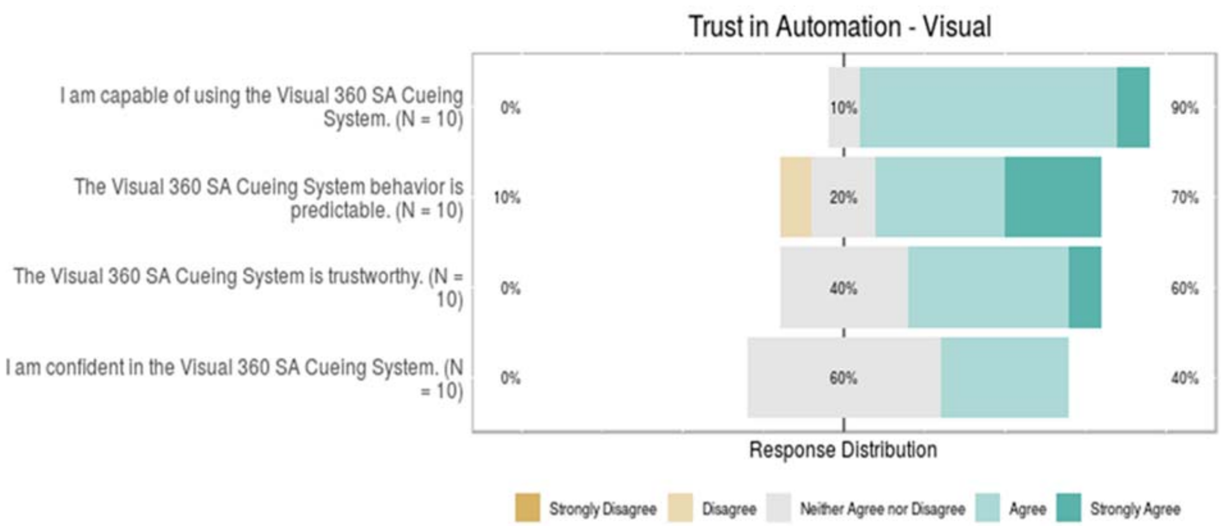


Figure 51. Trust in automation – visual cueing ratings.

Trust in Automation – Spatial Audio Cueing.

The responses for each of the four trust in automation questions for the spatial audio cueing were aggregated and grouped into positive, neutral and negative percentages for each question and are presented in Figure 52 below. The average trust in automation – spatial audio cueing rating was 3.95 out of a possible 5.0. Comments are listed in Appendix D.

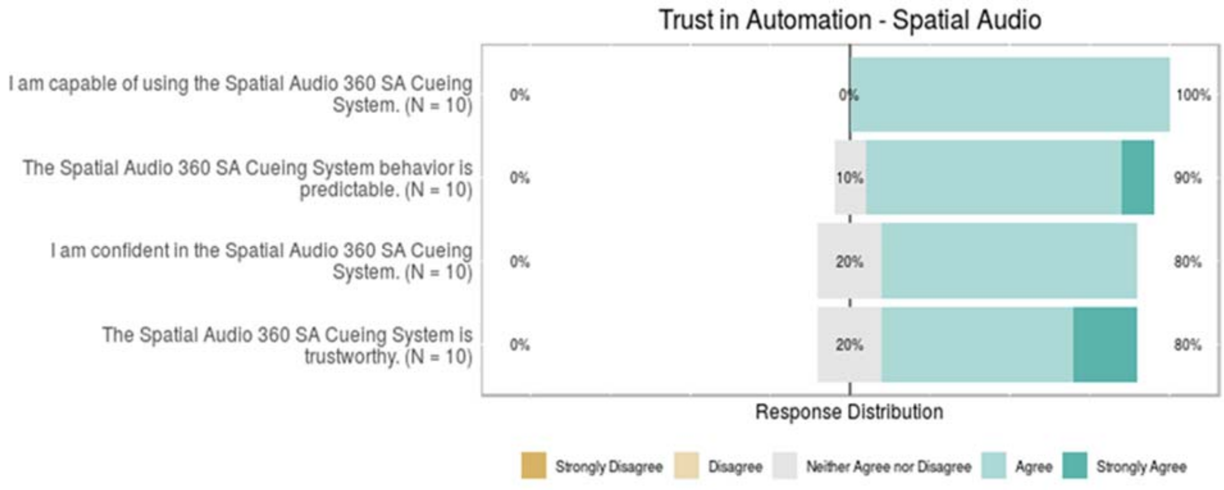


Figure 52. Trust in automation – spatial audio cueing ratings.

Trust in Automation – Tactile Cueing.

The responses for each of the four trust in automation questions for the tactile cueing were aggregated and grouped into positive, neutral and negative percentages for each question and are presented in Figure 53 below. The average trust in automation – tactile cueing rating was 3.83 out of a possible 5.0. Comments are listed in Appendix D.

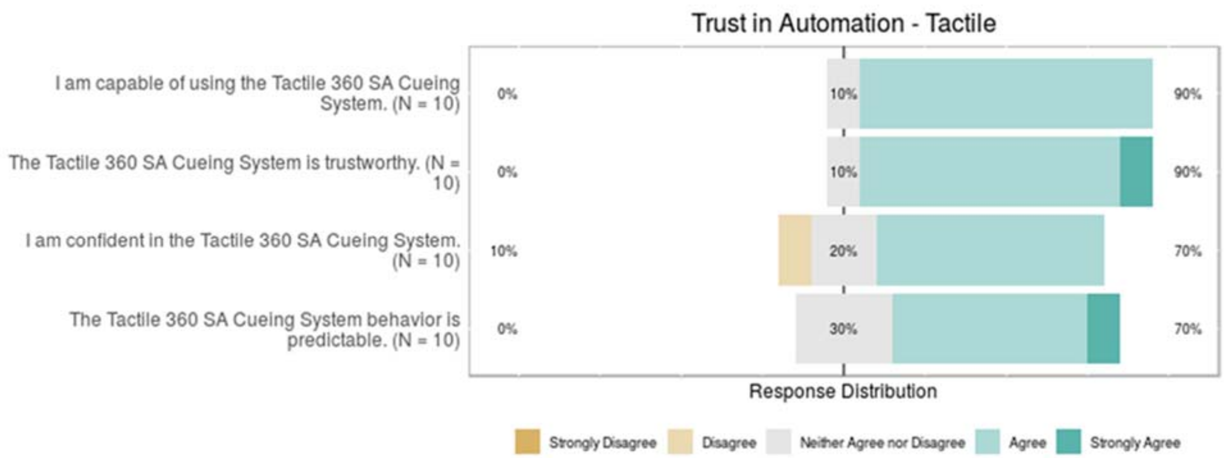


Figure 53. Trust in automation – tactile cueing ratings.

Motion Sickness Assessment Questionnaire.

Descriptive statistics for the Motion Sickness Assessment Questionnaire (MSAQ) are reported in Table 32 below. Since the MSAQ was only given at the end of the day, scores are reported by display type used for the day. As indicated in Table 32, pilots reported higher levels of motion sickness symptoms when flying with the HMD than with the PMD.

Table 32. Overall Motion Sickness Scores by Individual and Display

Pilot	Panel-Mounted	Helmet-Mounted
1	12.50	29.86
3	11.11	11.11
4	12.50	31.25
5	11.81	23.61
6	13.19	18.75
7	11.11	11.81
8	13.19	15.97
9	11.11	20.83
Mean	12.07	20.40

Discussion

The primary goal of this study was to evaluate the effect of multimodal cueing configurations on flight performance, workload, and situational awareness when exposed to obstacles on the flight path within an urban environment under DVE conditions. Overall, the flight performance data did not support a specific cueing configuration that improved obstacle detection and avoidance compared to the baseline cueing configuration. These results are confounded, however, by the effects of flight route and pilot variability on overall performance. Several lessons have been learned and trends were identified.

First, during takeoff a trend was noted for increased time spent within the Caution Region with an Urgent 1 obstacle present when flying with V, VA, and VT cueing configurations, as compared to the baseline flight when all configurations were compared. This trend persisted when the effects of layered cueing were examined. Similar trends were found during the approach phase, where more time was spent within the Warning/Rotor Region while an Urgent 1 obstacle was present when flying the VAT cueing configuration compared to baseline. One might expect pilots to avoid flight within Caution or Warning/Rotor regions. However, the trend of more time spent within these regions given additional cueing suggests that the cues enabled improved SA management and navigation near the obstacles. Results of the subjective SA measure was consistent with this rationale in that participants viewed their situational awareness higher in conditions in which cues were provided than when no advanced cueing was provided.

While the flight performance data did not indicate any impact of changes of workload level, participants' subjective workload ratings indicated that they viewed their overall workload lower in the advanced cueing conditions compared to baseline cueing only. This is an important factor given that finding the appropriate balance of cueing is critical to ensure the cueing itself is not resulting in additional workload. Moreover, given that these advanced cueing configurations were new to the pilots who were included in this study, it is promising to note that they did not rate workload as being excessive. Despite minimal training time (approximately five hours per participant over the course of two days), the participants believed that training was helpful, adequate and that they felt confident that they were trained appropriately.

Participants rated visual cueing usability favorably with highest ratings for intuitiveness. They rated the visual depiction of the power lines as very useful. Spatial auditory cueing was rated positively overall with the highest ratings for being clear, noticeable, intuitive and realistic. This result was also somewhat supported in the performance data with the trends for greater time spent within Caution and Warning/Rotor Regions occurring during conditions that included the spatial auditory configuration. Participants did indicate that they would like to have the ability to set user preferences such as the number and frequency of the audio alerts and being able to turn the display on or off. The tactile cueing was rated as clear, interpretable, and useful. Overall, performance ratings indicated that the participants believed that each cueing system provided congruent information. The ratings indicated that some form of the cueing was more beneficial to performance than no additional cueing, and in fact, the ratings were higher as two or more cueing types were provided. Obstacle detection was rated easier in the tri-modal (visual + auditory + tactile) than in the visual condition alone or the baseline condition. The visual + audio cueing condition was ranked highest in preference by the participants followed by the visual + audio + tactile condition. In third place was a tie between the visual + tactile and visual alone conditions. Coming in last, the baseline was ranked lowest in preference.

Finally, the participants rated trust in automation high for all cueing types indicating that they were capable of using this obstacle avoidance cueing automation, that this automation was predictable and trustworthy and that they were confident in these cueing systems. Thus, while the performance data was limited due to variability in routes, the subjective feedback of the cueing displays suggests that the cueing modality configurations examined each hold promise for future implementation. Despite having limited time for training, the pilots were able to trust the cueing displays assessed, which may be attributed to the intuitive nature of using the auditory and tactile modalities to deliver informational cues.

Limitations.

The results of this study are limited due to the use of different routes for the testing conditions. While this was done to ensure each pilot was not exposed to the same route twice, and therefore would not adopt expectations for obstacles within the route, it resulted in an imbalance of conditions flown across routes. This limitation was further compounded by the routes not being comparable in difficulty levels despite substantial efforts to maintain equal difficulty across routes. Indeed, analyses found that route was the main factor driving the variability within the data. Thus, we are limited in our ability to fully interpret the effectiveness of the cueing configurations on performance. Another limitation is the number of participants within the study, particularly given the number of testing conditions.

Conclusions

Taken together, there are no clear indications for which cueing modality is ideal, but there are patterns that suggest additional cueing may lead to favorable increases in performance. This trend was present in both the performance and subjective data. Further work is required to identify the ideal cueing combinations and parameters to use. A future study strategically examining the additional cueing configurations (VT, VA, and VAT), with carefully planned routes and obstacles, would likely yield more concrete results in terms of the ideal cueing configuration.

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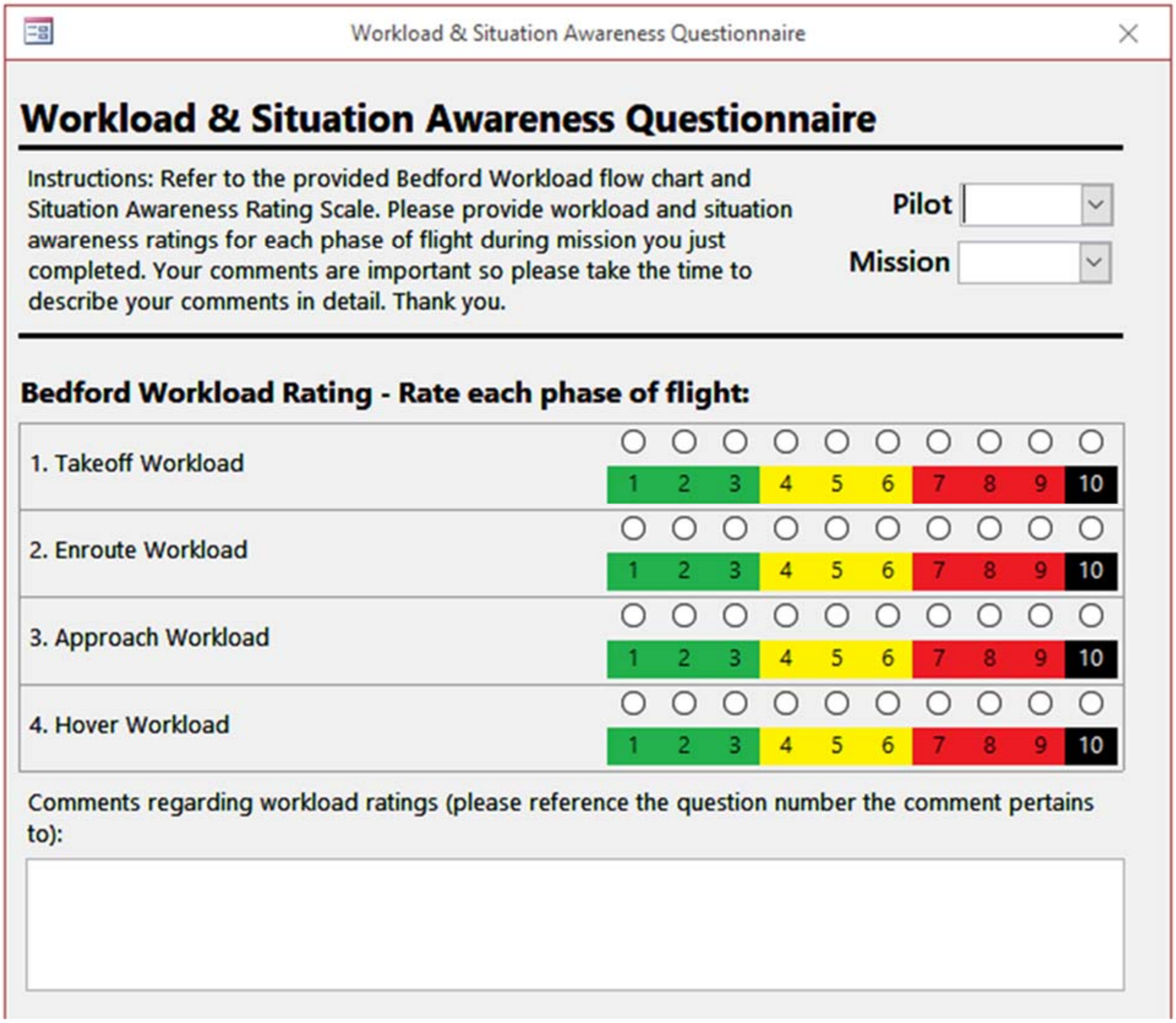
Appendix A: Acronyms and Abbreviations

DTIC	Defense Technical Information Center
HQ USAMRDC	U.S. Army Medical Research and Development Command
USAARL	U.S. Army Aeromedical Research Laboratory
WPG	Warfighter Performance Group

Appendix B: Workload & Situation Awareness Questionnaire



Workload & Situation Awareness Questionnaire

Workload & Situation Awareness Questionnaire

Instructions: Refer to the provided Bedford Workload flow chart and Situation Awareness Rating Scale. Please provide workload and situation awareness ratings for each phase of flight during mission you just completed. Your comments are important so please take the time to describe your comments in detail. Thank you.

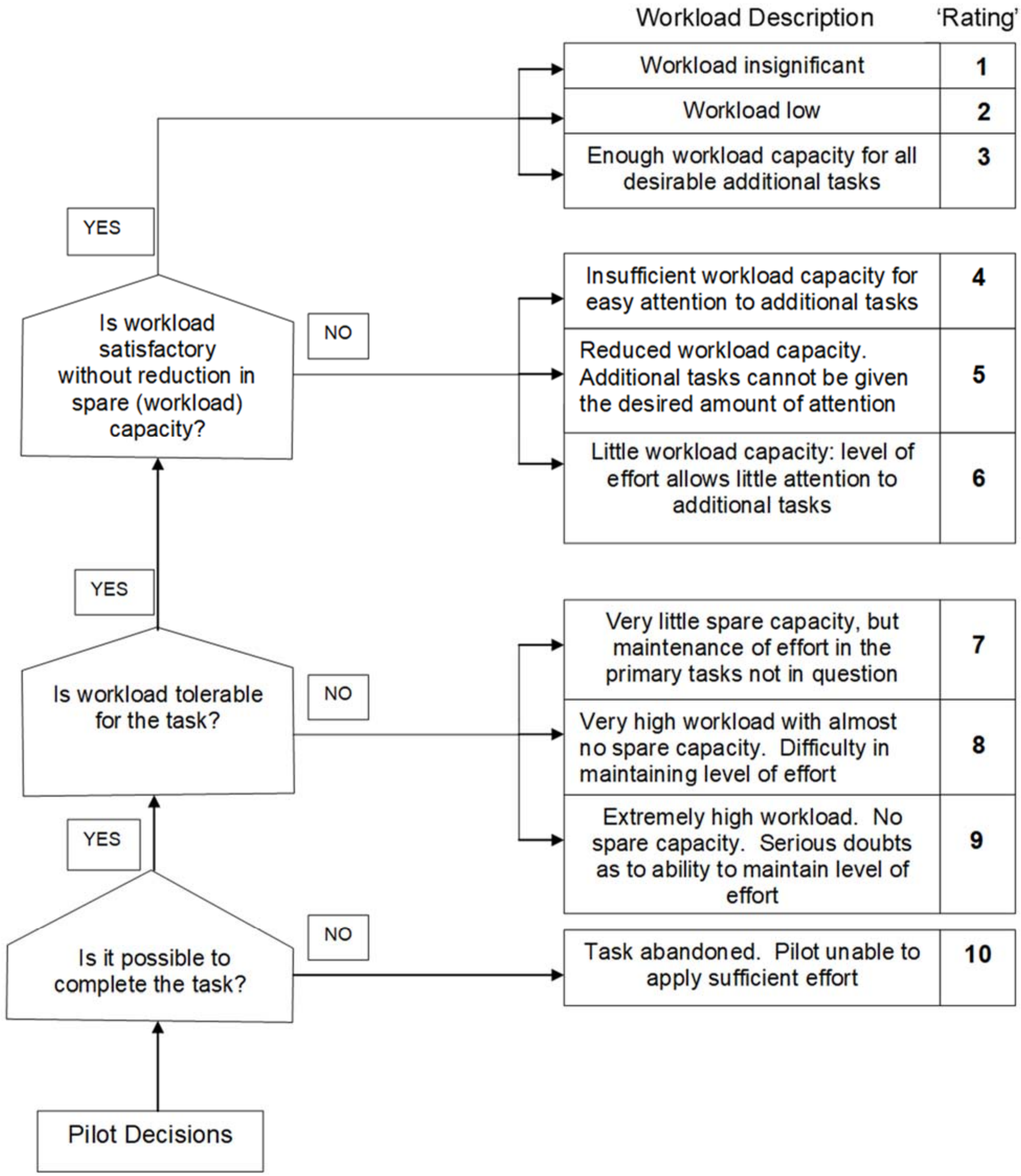
Pilot

Mission

Bedford Workload Rating - Rate each phase of flight:

1. Takeoff Workload	1	2	3	4	5	6	7	8	9	10
2. Enroute Workload	1	2	3	4	5	6	7	8	9	10
3. Approach Workload	1	2	3	4	5	6	7	8	9	10
4. Hover Workload	1	2	3	4	5	6	7	8	9	10

Comments regarding workload ratings (please reference the question number the comment pertains to):


Workload Description
'Rating'
Workload insignificant
1
Workload low
2
Enough workload capacity for all desirable additional tasks
3
YES
Is workload satisfactory without reduction in spare (workload) capacity?
NO
Insufficient workload capacity for easy attention to additional tasks
4
Reduced workload capacity. Additional tasks cannot be given the desired amount of attention
5
Little workload capacity: level of effort allows little attention to additional tasks
6
YES
Is workload tolerable for the task?
NO
Very little spare capacity, but maintenance of effort in the primary tasks not in question
7
Very high workload with almost no spare capacity. Difficulty in maintaining level of effort
8
Extremely high workload. No spare capacity. Serious doubts as to ability to maintain level of effort
9
YES
Is it possible to complete the task?
NO
Task abandoned. Pilot unable to apply sufficient effort
10
Pilot Decisions

Appendix B: Workload & Situation Awareness Questionnaire

Biometric Measures

The impact of the cueing modalities on pilot workload were objectively assessed using two biometric measures: electrocardiogram (ECG), to measure heart rate, heart rate variability and electroencephalogram to measure brain activity. These measures were selected for their responsiveness to workload, minimal invasiveness, compatibility with the testing paradigm, tolerance of the simulator environment, and potential utilization in aircraft. Additionally, pupillometry and eye tracking data were collected to assess gaze position and changes in pupil size, which correspond with workload.

Electrocardiogram.

Heart rate and heart rate variability (HRV) data were collected using the BioNomadix® system. This system recorded heart activity at a rate of 1,000 Hz. Pilots wore three electrodes placed on the torso and a wireless data transmitter. Data were post-processed offline using a custom peak-detection algorithm developed by USAARL to identify R-peaks in the QRS complex of noisy ECG recordings. The code was written in Python using the Numpy and Pandas libraries and was customized for processing large datasets in parallel. Metrics extracted for analysis included beats per minute and heart rate variability using the standard deviation of normal-to-normal (SDNN) beats.

Electroencephalogram.

The B-Alert X-24 wireless wet electrode system was used to record EEG activity. The X-24 incorporates 20 channels corresponding to scalp locations according to the International 10-20 system (frontal channels: Fp1, Fp2, F7, F3, Fz, F4, F8; central channels: C3, Cz, C4, T3, T4; parietal and occipital channels: P3, POz, Pz, P4, T5, T6, O1, O2). Power spectral density (PSD) values were computed using the automated algorithms provided through the B-Alert Live Software (Advanced Brain Monitoring, 2009). Prior to computing PSD values, artifacts were identified and removed using the ABM algorithms for artifacts associated with electromyography (EMG), eye blinks, excursions, saturations, and spikes (B-Alert Live, 2009). The EEG system selected provides workload classifications to be used for data analysis. The workload classifications provided include a raw workload probability (value ranging 0 to 1), with a higher probability reflecting higher workload. The workload classifications are derived using a linear discriminant function analysis (DFA) with two classes, high and low workload. EEG data from channels C3C4, CzPO, F3Cz, FzC3, and FzPOz are used to calculate the classification (Berka et al., 2007). Cognitive state classifications examined in in the study included engagement, workload based on the forward-backward digit span (workload FBDS), and average workload (ave workload).

Eye Tracking and Pupilometry. Eye tracking and pupillometry data were collected using the EyeWorks Record (EyeTracking Inc.) software package simultaneously with two additional software modules, the Scene Camera Module and with the Index of Cognitive Activity (ICA) Module. The Scene Camera Module allows the pilot's calibrated gaze position to be overlaid onto a forward-facing video feed collected by a small camera mounted to an overhead control panel, just behind the pilot. The EyeTracking Inc.'s trademarked (Marshall, 2007) ICA Module provides both real-time and post-collection analyses of the pilot's mental workload throughout the session. The ICA is expressed as a value between 0 and 1, with 1 representing the highest level of cognitive workload. These data were compiled and analyzed offline to generate the figures presented below in the results section.

One Fovio FX3 camera was positioned to be used for panel mounted (PMD) display testing while the other Fovio FX3 camera was positioned to be used for head mounted display (HMD) testing (see Figures XX). For the PMD configuration, the camera was mounted to the forward panel just below the flight instrument displays (Figures XX). In this configuration, the camera provided accurate and reliable eye-tracking signal quality for nearly all of the pilots tested. Data presented below detail the ICA-calculated workload from these data in 6 of the 8 pilots tested in the present study. Data were successfully collected from the remaining 2 pilots, but a software bug during post-collection processing prevented ICA calculation for these data sets. EyeTracking, Inc. is addressing this issue and the analysis of these data will be completed when a solution is provided.

In the HMD configuration, the Fovio FX3 camera was positioned directly in front of the pilot (Figures XX). In this configuration, the camera was able to penetrate the HMD to reliably track the eye position and pupil size when the pilot was looking straight ahead. However, this was not the case when the pilot was looking off axis; that is, looking around to take full advantage of the HMD expanded field-of-view. Consequently, the eye tracking system was not able to produce reliable data to support ICA calculations during the HMD sessions; thus those data are not presented in this report. This limitation will be overcome in future studies by using a recently-obtained, HMD-mounted, camera system to ensure reliable eye-tracking signals over the entire field-of-view.

Figure 54. Cockpit with Eye Tracking Cameras in Place.

Figure 55. Cockpit with Cameras for HMD and PMD use.

Appendix C

Biometric Results

Workload classifications from the EEG, heart rate, and heart rate variability were analyzed using repeated-measures analysis of variance (ANOVA). Aggregated data for each phase of flight were compared across cueing configurations and are reported by phase below.

Taxi Configuration Analyses of Biometric Measures

During the taxi phase there was a statistically significant difference for the Ave. Workload metric, F (4, 28) = 2.80, p = 0.05, ω2 = 0.02. Planned comparisons showed a significant difference between the baseline and VA, t (28) = 3.01, p = 0.02. See Table X below for all descriptive statistics. There was not a significant effect of configuration on HR and HRV metrics, see Table 33 for descriptive statistics.

Table C1. **Configuration Effect on Biometric Data during Taxi Phase**

	BL		**V**		**VA**		**VT**		**VAT**	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Engagement	.47	.02	.48	.02	.45	.02	.46	.02	.48	.02
Workload FBDS	.79	.01	.80	.01	.82	.01	.80	.01	.80	.01
Ave.Workload	.74	.01	.74	.01	.76	.01	.75	.01	.74	.00
Heart Rate	10.39	0.85	11.40	1.09	9.61	0.52	8.74	0.49	8.72	0.88
Heart Rate Variability	3.42	3.69	11.39	5.70	1.64	5.47	18.45	10.0	9.02	6.00

All mean and SE values are the sample statistics across all flights.

$\chi 2$ and p values given below are based on the mixed effects models that account for the repeated measurements and within subject variance.

En-route Configuration Analyses of Biometric Measures

There were no significant effects of configuration found for the EEG metrics, although there was a trend towards significance for the average workload metric. See Table X below for descriptive statistics.

Table C2. **Configuration Effect on Biometric Data during En-Route Phase**

	BL		V		VA		VT		VAT	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Engagement	0.47	0.02	0.47	0.02	0.43	0.02	0.43	0.02	0.45	0.02
Workload FBDS	0.79	0.01	0.77	0.01	0.80	0.01	0.78	0.01	0.79	0.01
Ave.Workload	0.74	0.01	0.71	0.01	0.74	0.01	0.73	0.01	0.73	0.01
Heart Rate	9.30	0.67	9.42	0.87	8.19	0.50	8.25	0.45	7.32	0.75
Heart Rate Variability	4.18	5.52	4.70	4.38	-0.69	7.68	6.79	8.98	20.38	10.78

All mean and SE values are the sample statistics across all flights.

$\chi 2$ and p values given below are based on the mixed effects models that account for the repeated measurements and within subject variance.

Approach Configuration Analyses of Biometric Measures

There were no significant results found within the EEG metrics, nor the HR and HRV metrics (see Table X for descriptive statistics).

Table C3. **Configuration Effect on Biometric Data during En-Route Phase**

	BL		V		VA		VT		VAT	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Engagement	0.48	0.03	0.44	0.03	0.45	0.01	0.46	0.04	0.47	0.03
Workload FBDS	0.79	0.01	0.79	0.01	0.82	0.01	0.79	0.01	0.80	0.01
Ave. Workload	0.75	0.01	0.74	0.01	0.77	0.01	0.74	0.01	0.75	0.01
Heart Rate	13.67	1.10	14.85	1.29	12.41	1.06	12.91	0.74	11.71	0.91
Heart Rate Variability	-13.29	6.02	-12.64	5.74	-12.35	3.48	9.83	6.39	-20.26	4.55

All mean and SE values are the sample statistics across all flights.

$\chi 2$ and p values given below are based on the mixed effects models that account for the repeated measurements and within subject variance.

Landing Configuration Analyses of Biometric Measures

There were no significant effects with EEG data. See Table X for descriptive statistics. The effect of cueing was significant on HRV values, $F(4, 28) = 2.97$, $\omega^2 = 0.07$. Paired contrasts using the Dunnet test showed a larger increase in HRV values during the V configuration compared to BL. See Table X below for descriptive statistics.

Table C4. **Configuration Effect on Biometric Data during Landing Phase**

	BL		**V**		**VA**		**VT**		**VAT**	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Engagement	0.47	0.03	0.46	0.03	0.43	0.02	0.43	0.04	0.41	0.04
Workload FBDS	0.83	0.01	0.82	0.01	0.84	0.01	0.83	0.01	0.82	0.01
Ave. Workload	0.77	0.01	0.77	0.01	0.79	0.01	0.80	0.01	0.77	0.01
Heart Rate	4.78	1.15	18.21	1.83	13.48	0.96	14.36	1.06	13.22	0.90
Heart Rate Variability	-4.32	3.41	6.89	9.26	-3.06	4.58	-10.89	6.85	-6.77	5.49

All mean and SE values are the sample statistics across all flights.

χ^2 and p values given below are based on the mixed effects models that account for the repeated measurements and within subject variance.

Eye Tracking and Pupillometry Measures.

Gaze position information can reflect pilot familiarity with a particular avionics layout as well as pilot cognitive workload (for review see: Peißl, Wickens, & Baruah, 2018). Image 3 provides an example of how gaze-position can reflect pilot familiarity and cognitive workload. The gaze trace in Image 3A displays the pilot's first attempt navigating a nap-of-the-earth obstacle course using the ICE avionics layout. As is evident, the pilot often looks at display regions containing no navigation-relevant task information. This trace shows an inefficient scan pattern. The gaze trace in Image 3B reflects the same pilot's fourth attempt using this avionics layout. At this point in the experimental session, a more consistent and efficient scan pattern is emerging. Clearly, the pilot looks less frequently at task irrelevant areas of the PMD. Metrics designed to measure this phenomena can quantify a pilot's familiarity with the new avionics layout and provide feedback regarding the pilot's comfort and familiarity with the symbology set.

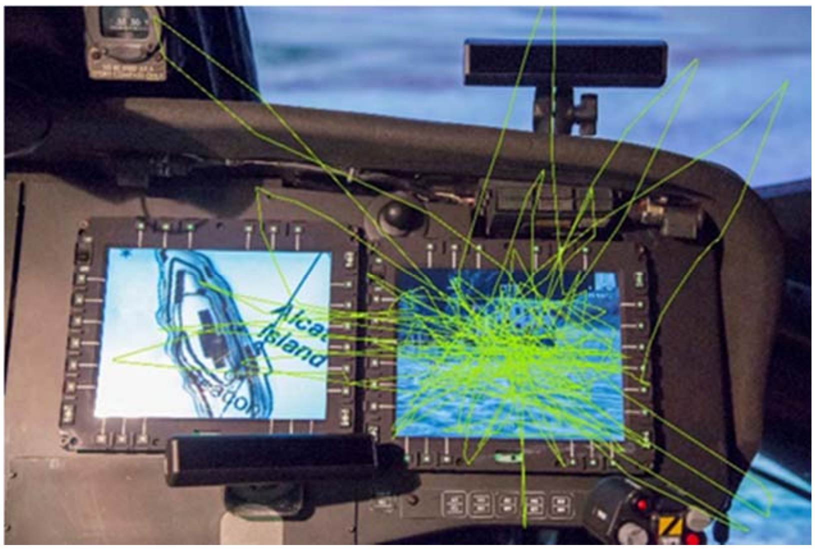


Figure C1. First exposure.

Figure C2. Last exposure.

It should be noted that traces in Image 3A and B are not typical raw data. Rather, they were recreated from filtered and realigned gaze position data recorded during the en-route phase of flight for a single pilot with the highest quality and consistency of gaze position data. While these data in Image 3A & Image 3B are useful for demonstration and proof of concept, the dataset is small, and is thus not sufficiently powered for statistical analysis.

Figures 1 – 5 show the ICA calculated workload for each of the 5 flight phases, averaged across-subjects, for each of the cueing configurations. The error bars represent Standard Error of Means, and show a large amount of variability in mental workload between subjects. In Figure 1, the characteristic cognitive workload profile is evident; the same general profile is seen in Figures 2 through 6. The highest levels of cognitive workload emerge during the phases of flight in which the pilots found themselves transitioning from the ground to the air and navigating around obstacles while in very close proximity to the ground. Sine these are regarded as the most difficult and dangerous operations, these data suggest that the ICA algorithm is sensitive to the increased effort required to navigate these scenarios. Unfortunately, the sensitivity of the ICA metric is not sufficient to overcome the inter-subject variability and small sample size, and does not provide clear distinctions between the different cuing configurations. Figure 6, which combines the data from Figures 1-5, suggests that the presence of tactile cuing during the taxi phase may produce higher workload scores in the pilots tested. The tactile warning system sensitivity range was such that several pilots reported near continuous signaling while in the taxi phase of flight due to the close proximity of the obstacles. These data could suggest reconfiguring the sensitivity range of the tactile warning system during these periods to prevent task saturation.

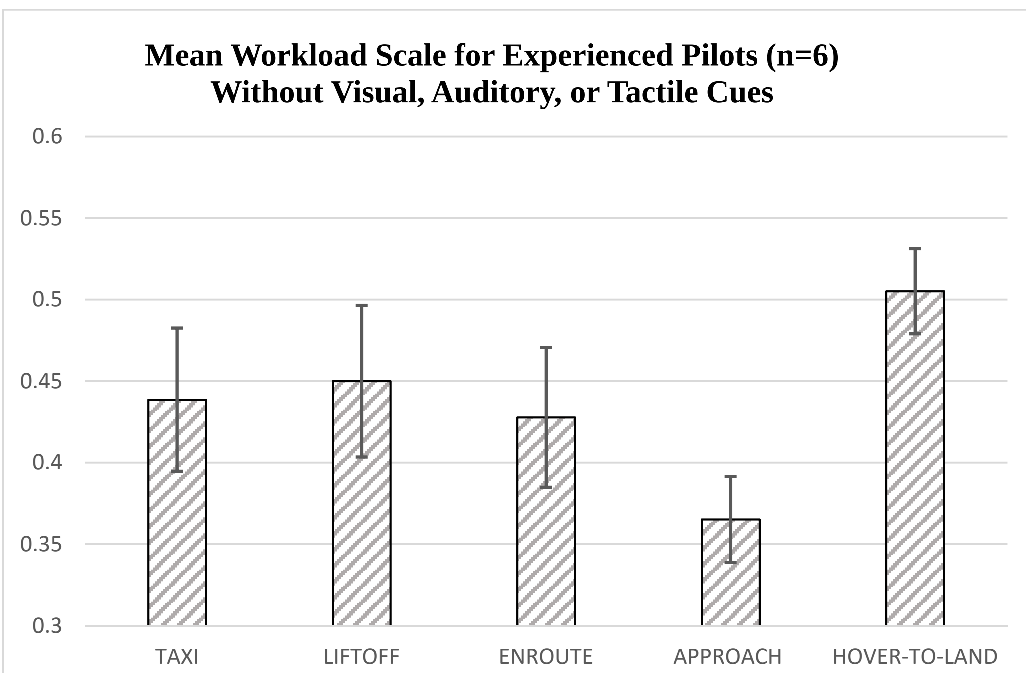


Figure C3. Mean ICA workload scores by phase of flight for experienced pilots (n=6) using panel mounted displays to navigate in a degraded visual environment using a full-motion blackhawk simulator without the assistance of visual, auditory, or tactile cue.

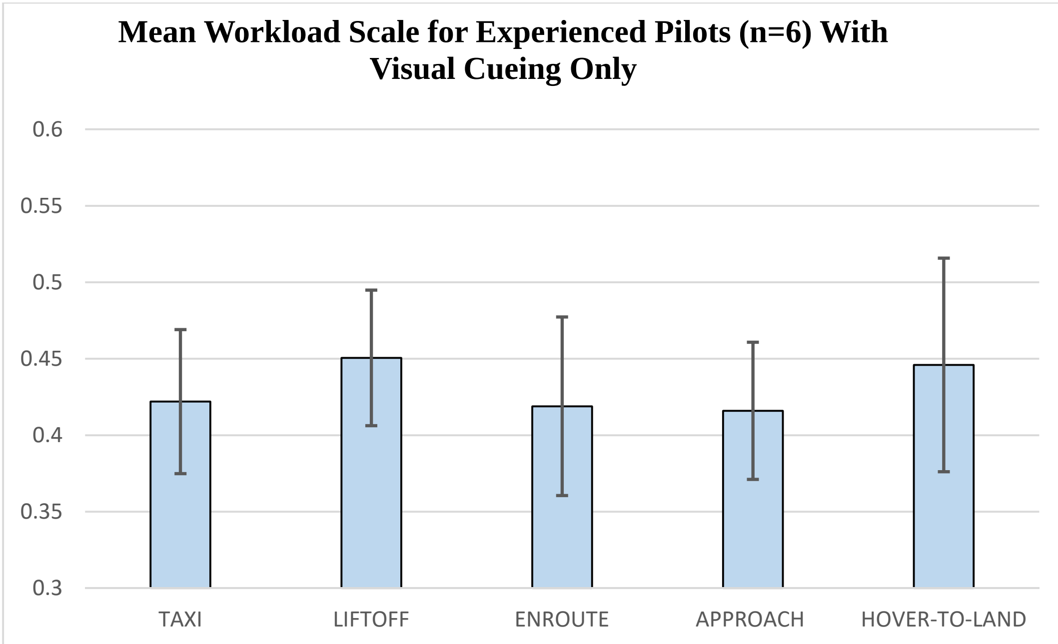


Figure C4. Mean ICA workload scores by phase of flight for experienced pilots (n=6) using panel mounted displays to navigate in a degraded visual environment using a full-motion blackhawk simulator with the assistance of only visual collision cueing

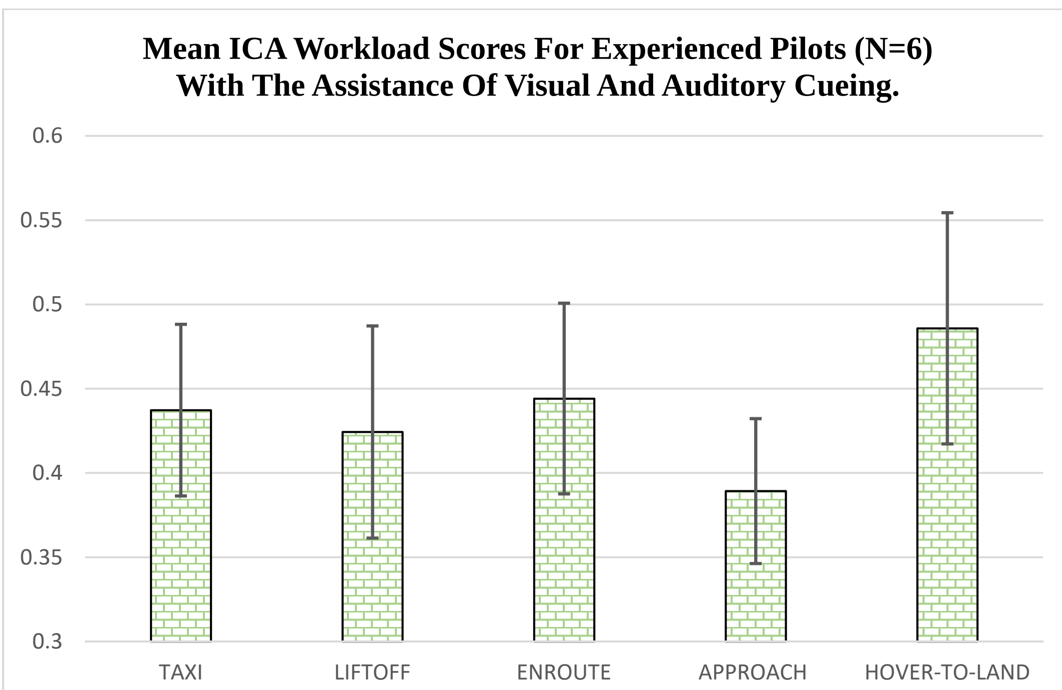


Figure C5. Mean ICA workload scores by phase of flight for experienced pilots (n=6) using panel mounted displays to navigate in a degraded visual environment using a full-motion blackhawk simulator with the assistance of visual and auditory collision cueing.

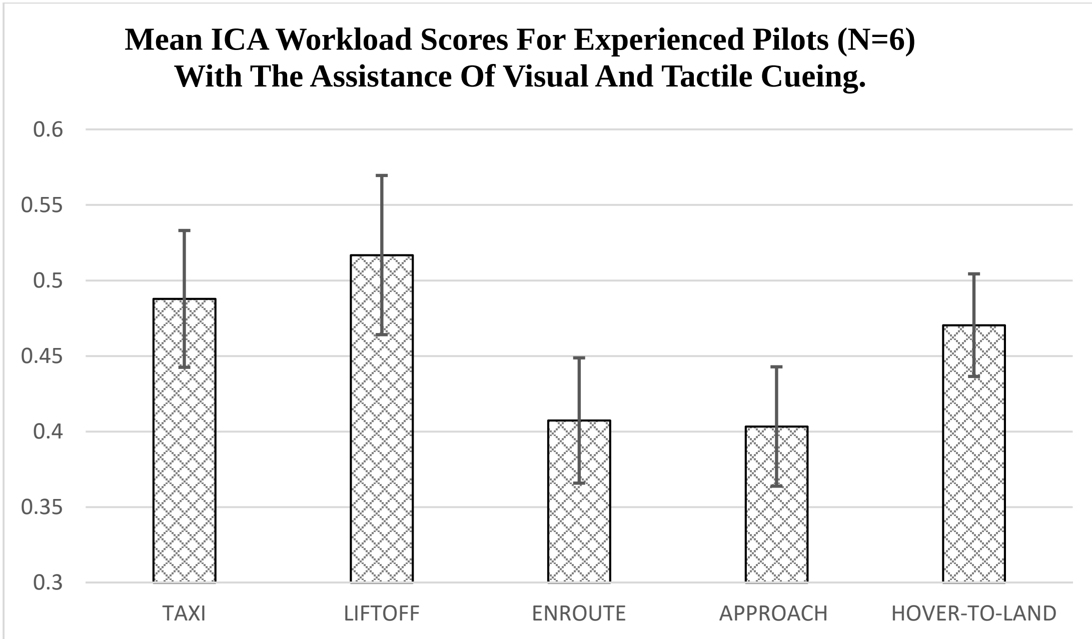


Figure C6. Mean ICA workload scores by phase of flight for experienced pilots (n=6) using panel mounted displays to navigate in a degraded visual environment using a full-motion blackhawk simulator with the assistance of visual and tactile collision cueing.

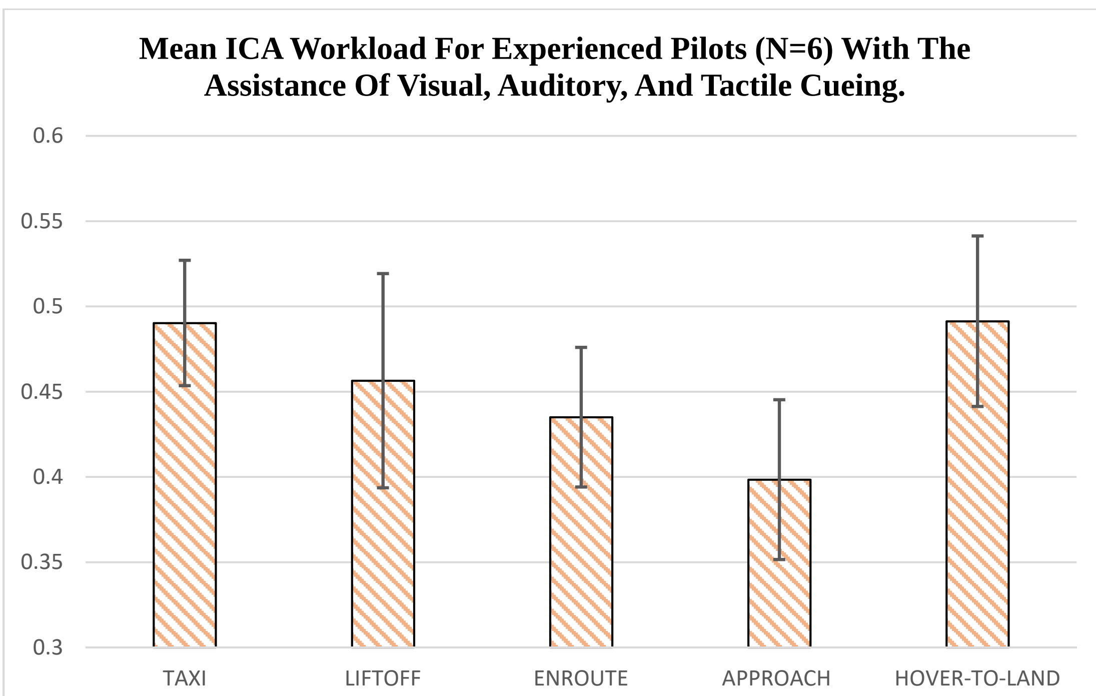


Figure C7. Mean ICA workload scores by phase of flight for experienced pilots (n=6) using panel mounted displays to navigate in a degraded visual environment using a full-motion blackhawk simulator with the assistance of visual, auditory, and tactile cueing.

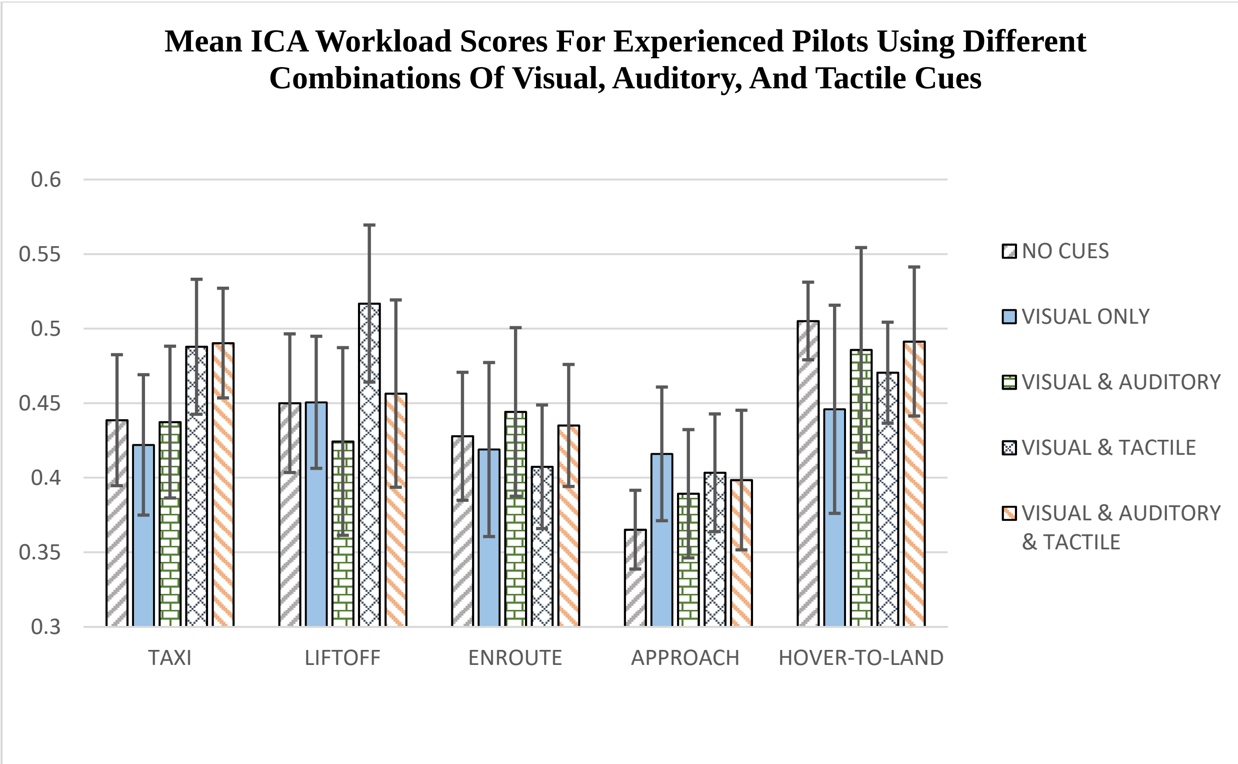


Figure C8. Mean ICA workload scores by phase of flight for experienced pilots using panel mounted displays and different combinations of visual, auditory, and tactile cues to navigate in a degraded visual environment using a full-motion blackhawk simulator

Appendix D

Subjective Comments

Table D1. **Combined Observer Notes, AAR and Survey Comments on Visual SA Diamonds Symbology (Outboard)**

Pilot	Comments
1	Maybe seconds or distance to impact displayed would be helpful. Used diamonds to tell me that something was in my path. Didn't pay attention to color change. Would like distance from obstacle. That would be useful. I think the diamonds did provide the enhanced SA. Didn't notice color change as much as auditory change. I'd like to have a distance number next to diamond. All other (obstacles other than wires) obstacles I was able to see before 'hearing' them.
3	No comments.
4	No comments.
5	Visual symbology seemed to pop up too late, TTC was too quick. Good symbology set for the diamonds.
6	Helpful. Liked size scale as you get closer. Hard to discern colors. Make more distinct
7	Make the visual cues (diamonds) more different. Different colors to more easily differentiate between caution and warning
8	Thought the threat indicators were great size in the diamonds. Did not notice that the diamonds changed colors
9	Sometimes he noticed the color and size change. He was more focused on the route.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D2. **Combined Observer Notes, AAR and Survey Comments on Visual SA Wires Symbology (Outboard)**

Pilot	Comments
1	Wire symbology was hard to depict, may have it a little more prominent or a different color… Visual feedback for wires could be more distinct. Would like to see the wires have that same (color) type of thing [as cheverons]. More of like a neon color. Can wire height be displayed on either ICE page or Visual symbology page? I'd like to know how high (with numbers) the wires are. Wires: Enhance thickness or color of wire. I could hear it before seeing it. Make them more noticable. Neon. Information on how high those wires are would be great, either on inboard or outboard. Knowing the height will help me know how much space there is between wires and how high I can go. I was able to detect wires by hearing them much earlier than visual identification. All other obstacles I was able to see before 'hearing' them.
3	Hit wires on baseline. Focused on ground track. Lost sight of wires during baseline. Disorienting the way the wires ran parallel to aircraft. Power line indications remained well beyond passing them. Passing a set of power lines and still listening to the audio when they are a mile behind me at 70 knots is distracting. Power line clearance could also have a third level of clearence between the 0 feet and 30. The intent to stay low for enemy threat makes me want to be as low as possible to the obstacle and clearing by 30 feet or more was more altitude to correct after clearing the obstacle which then prolongs my exposure to enemy threats.
4	Liked wire symbology - take a look at colors red (clearance line) on green blends at night. Horizon line obscures it. Difficult to see wires in baseline. Very close.
5	Fixated on wire symbology and didn't correct. Crashed into wires. Wire crossing alerts were very beneficial. Wire symbology was really good.
6	HMD: Flight path marker is pretty cool. Horizon line covers powerline dashes. Solution should be to prioritize powerline over horizon. Colors were good. Make colors match on inboard and outboard. Make them wires on top of ICE. It got lost.
7	Crossing the wires, it would be nice to know a numerical reading of how much I am clearing it. Maybe the wires could just be two colors, like maybe a caution and a warning or a digital readout of what my altitude is above the wires. More colors to judge how "clear" I am. Example red=below up to 10ft above, yellow= 10ft above to 30 feet above, blue=greater than 30 feet above. Or a digital readout showing my elevation in relation to the wires (+33ft, -15 feet etc). Power line colors could give me more information. For example, red power lines could indicate below the power lines up to 10ft above. Yellow could indicate 10ft above up to 30ft above. Blue could indicate above 30ft. Digital readout of clearance height could also be useful (+35ft, -8ft).
8	HMD: I really don't like the wires being blue. They were kind of hard to see. Would like to see the wires a little more bolded. The color change for the wires was well noticed.
9	Good and depicted exactly where they were supposed to be.
10*	Helpful. Would prefer powerline color to turn red if a/c is below the wires.
11†	No comments.

Note. *Pavehawk †AH-64

Table D3. **Combined Observer Notes, AAR and Survey Comments on Visual SA Overall Symbology (Outboard)**

Pilot	Comments
1	I was resistent to it at first but the capability that these cues give you is a pretty amazing capability. I did not see that obstacle soon enough (tower). Haze level when you get high makes it difficult to see. There is so much good info on the ICE, [SA on the Outboard MFD], that I didn't feel like I needed it. The ICE, [SA on the Outboard MFD], screen displaying the visual symbology (diamonds and wires) is better for obstacles.
3	Generally pleased with symbology. Need more work on satisfying cues with flight controls. Adjust cueing based on aircraft (tail, side, or nose). Right now it's based on the CG. Different clearances for different aircraft areas. On the M and L models, 8 pages - able to declutter and customize pages.
4	Visual - Useful didn't need numbers though. The enroute portion was good. Still no situational awareness to what is to your left and right but bood. The approach phase was cluttered and did not pick up obstacles between me and the LZ until to late.
5	HMD condition: Symbology is really good. The heading was good. Getting more familiar with it. HMD: Did not see tower on approach. Slightly below aircraft and wasn't picked up. Seems to work as intended, but may not be enough SA. HMD V+A: Towers felt like they came up without notice. Liked a standard symbology for obstacles.
6	The visual cueing during the approach phase appears to give you a clear path to intended point of landing. Many times there were obstacles between the aircraft and the landing site that were not depicted.
7	I feel like there are some obstacles that I'm not getting cueing for that I think I should be getting cueing for. (mostly below the aircraft). The stadium lights that we just went right over would have been good to know about (likely in ground rejection range). HMD: The blue wire lines are difficult to see far away. I really missed have the audio and tactile around all of those helicopter. In the last one, I felt like the audio was just to much, but not having it, I wish I did have some of it. Maybe there could be some sort of happy medium. Initial audio then tactile when closer but stop audio. Should be cueing me on the crane obstacle…or at least I'd like it to. It was kind of refreshing to have a lot of that audio and symbology stuff gone. I'd like to have been able to pause it have the view of what it looks like with no cues and then quickly switch over to having cueing so I can see what the cuing would be giving me. I'd be able to make a better comparison. I rely on visual cueing more than other senses, so I would like more predictability in order to have more confidence in the system.
8	Liked the Visual and 3D audio especially once adjusted in threattune at the end.
9	Some of the other stuff is hard because there's nothing you can do about the terrain or the obstacles - it lets you know about stuff that you can't do anything about. Some of the other stuff is a bit excessive - lets you know about things you can't do much about, like obstacles, and have to just jerk out of the way. Would like to know about obstacles further out. MMD's aren't showing on obstacles.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D4. **Observer Notes, AAR and Survey Comments on Visual SA Route Symbology (Inboard MFD)**

Pilot	Comments
1	Only glanced at visual symbology page to see overall route (navigational reference not obstacle avoidance). I'm using the visual symbology screen, I'm using it, but for only route path and location of wires. The only information that the HMD didn't have was the route, so I did look at the ICAD for that.
3	Good for route managament and powerlines.
4	No comment.
5	Used inboard PMD to monitor flight path. Helped with flight path.
6	Sometimes used it for flight path in urban environment.
7	Rarely used other than to verify I'm on route.
8	Occasionally I would use the inboard display to view the flight path and my location relative to it.
9	No comment.
10*	Likes the inboard MPD cueing for the route when trying to determine the route locations in difficult areas.
11†	No comment.

Note. *Pavehawk †AH-64

Table D5. **Observer Notes, AAR and Survey Comments on Visual SA Obstacle Lines Symbology (Inboard MFD)**

Pilot	Comments
1	Only glanced at visual symbology page to see overall route (navigational reference not obstacle avoidance).
3	No comments.
4	No comments.
5	No comments.
6	Only occasionally looked at lines to threat.
7	Symbology is intuitive, but not necessary as I don't want to be staring at that display for very long. Quick glances are all I would want to use it for so only really the route and wire obstacles were used.
8	I did not use it for the threat detection areas AT ALL.
9	Did not notice the lines shooting out for the obstacles.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D6. **Observer Notes, AAR and Survey Comments on Visual SA Wires Symbology (Inboard MFD)**

Pilot	Comments
1	If I lost sight of wires, maybe I would look at it.
3	Good for route managament and powerlines.
4	Was useful for wires locations. May be good to correlate wire colors with outboard display.
5	Used the inboard display for wire clearance. Helped with wires to cross check.
6	Used it everytime you heard wires to cross check where they were located.
7	Verified the location of a set of wires after getting the audio cue.
8	Display was primarily used for wires. As soon as I received the auditory rep for the wires I would scan the inboard display to see where the wires were relative to my flight path.
9	Nice bc sometimes it was hard to tell where they crossed.
10*	No comments.
11†	Noted that he missed not having the wire audio cue.

Note. *Pavehawk †AH-64

Table D7. **Observer Notes, AAR and Survey Comments on Visual SA Threat Rings Symbology (Inboard MFD)**

Pilot	Comments
1	Smaller threat detection circle. Improve threat page to show more valuable information. Allow for adjustments for detection and alert to be pilot dependent.
3	Used it some. Not necessarily for the threat ring. Make bowling pin outline more square at the end (triangular). The fat areas could pick up too late.
4	No comments.
5	No comments.
6	Never paid attention to threat space shape.
7	No comments.
8	No comments.
9	No comments.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D8. **Observer Notes, AAR and Survey Comments on Visual SA Overall Symbology (Inboard MFD)**

Pilot	Comments
1	I didn't use this at all. Less than 10%. Only for route confirmation and location of the wires. Whether they were paralleling my route or running through my route. I didn't use it for obstacles. Everything was in the outboad display. Plus didn't have time to reference it. It would be good for the non-flying pilot. Used the diamonds on the outboard. They were beneficial. Maybe I would use it more if the map was more detailed or you could zoom in and out. I only used threat space for flight route confirmation. Would also use it to determine wire location, but was not heavily reliant on information from the threat space. Found 80% of the information displayed to be relevant, but not useful or relied upon.
3	Map display is not as good as current aircraft map. Prefer higher detail map, would improve usage.
4	Inboard PMD - difficult without that in baseline. Still able to use it with HMD liked the inboard page.
5	Happy with symbology and presentation of symbols. Would occasionally check to compare to flight path when threats would come up. Did not use much for hover symbology.
6	Route E, HMD V: TP23 .08NM…..unexpected red bar on SA symbology Would like the ability to zoom in and out.
7	Almost never used with the HMD.
8	No comments.
9	No comments.
10*	Did not use. Task saturated with other cueing and maneuvers.
11†	No comments.

Note. *Pavehawk †AH-64

Table D9. **Observer Notes, AAR and Survey Comments on Aural Cueing**

Pilot	Comments
1	Once those wires are behind me, I have no need to hear them. It's kind of a distraction once the are behind me. That is pretty annoying right there. Detracts from anything else. (having the 3D audio with wires running parallel for a bit). Wire sound behind me is not of any use. Just distacts. Obstacles and wires. In hover, rear audio is good, but in forward flight, get rid of rear audio. I could hear the audio change from the low to the high which would have more urgency for me. I was getting too many cues. I adjusted ThreatTune after my trials. Better for low airspeeds and hover operations. Most valuable piece of information was the audio alerts while hovering. The two tones kind of blended in with each other during higher speeds (70 knots). Was distracting enroute. After passing an obstacle I would still hear the obstacle behind me. That was very distracting. Don't need that. The same for approach and landing. I was unable to determine vertical location of obstacle from auditory tone alone. I was able to detect wires by hearing them much earlier than visual identification. spatial audio would sometimes blend together.
3	Doesn't want to hear wires after passing. Pleased with the audio. Would prefer an acknowledge button. Buzzing behind with wires is not necessary. May prefer a mode switch to guide for landings. (response to question 20) depending on how the power line audio would be I would like to hear it. If it was a simple audio beeping tone that is intermixed with all the other beeps then I do not want to add to the clutter. power line indications remained well beyond passing them. Passing a set of power lines and still listening to the audio when they are a mile behind me at 70 knots is distracting.
4	Recommended a little further detection distance. Helped to identify better. Audio is somewhat distracting due to monitoring radio calls. In isolation there is benefit. The wire audio was very useful.
5	Left CEP loose, but not affecting sound. Liked the caution to warning, tones were good, spearate the frequencies. Useful, sometimes distracting in heavy operating environment. Able to distinguish over ATC traffic.
6	Audio overload/clutter. Direction and distance to obstacle I would give a plus. Distracting in urban environment. Too much. Want the ability to turn off. Audio enroute. Overwhelming at times with multiple structures all around aircraft. It would be nearly impossible to hear crewmembers at that point.
7	The wires are distracting and annoying if they are on for too long. (the audio). It was kind of refreshing to have a lot of that audio and symbology stuff gone. I'd like to have been able to pause it have the view of what it looks like with no cues and then quickly switch over to having cueing so I can see what the cuing would be giving me. I'd be able to make a better comparison. Appropriate, no issue with distance. Better after I made changes to the parameters in the last trial. Very useful as an initial notification, but is distracting over a long Period. May be less distracting if aural handed off to tactile after the initial notification of a hazard. With the ability to select the distance and time thresholds, I believe once the most desireable threshold is found, it should be standardized for every aircraft.That way different crew mixes would still be trained to hear cautions and warnings at the same thresholds.
8	In a tactical environment, I'd like to have the ability to just mute the audio with one button if needed. Also, once it gives me an audio warning, don't keep giving me the audio. Distance needed to be extended to about 9 to 10 seconds and could be reducted in volume slightly. The wires were way to loud and need to add functionality to be able to me muted by the pilot. Also

Pilot	Comments
	the wires needed to be muted once crossed. Liked the Visual and 3D audio especially once adjusted in threattune at the end. Have the ability to mute or dim the power line sound once you hear it for a second or so. There needs to be a way to mute the audio for the wires or at least dim the volume. The detection space around the aircraft at a hover needs to be made smaller or at least adjustable. Make initial volume for wires loud then after a second or two reduce sound. #23. During flight at low level down roads when every building is a close in hazard the sonifications because annoying and overpowering. Also the wire sonification needs to mute as soon as the aircraft is past the wires in forward flight.
9	Likes the powerline noise -" that's pretty nice". Good. Useful and distracting...both at times, flying in between buildings - annoying and too distracting.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D10. **Observer Notes, AAR and Survey Comments on Tactile Cueing**

Pilot	Comments
1	Tactile: more useful during hover taxi (more than audio and visual), I could take info and make quick adjustment. During enroute not enough time to react. Tactile was best for low speeds like during taxi. I probably used tactile cuing the least. Valuable in low airspeed and hover operations, but not at higher speeds enroute and approach. Could be replaced by audio cueing. It is a lot easier to react to what I hear more than what I feel. Was reading the takeoff pad as an obstacle. It was comfortable and I could distingush direction. Seat buzz to arrest descent was good. It was difficult to immediately associate vibrations with direction of obstacle except at low airspeed or during a hover. I would often 'feel' the obstacle before seeing it during low airspeed/hover operations. It was difficult to immediately associate vibrations with direction of obstacle except at low airspeed or during a hover. I would often 'feel' the obstacle before seeing it during low airspeed/hover operations
3	Uncomfortable tactile cues. Doesn't like the seat pan tactors. May be too sensitive. No tactors, but when coming down it may be good to have tactors stimulate when you are over an obstacle in approach phase to be sure you clear obstacles. Would like a tactile cue that could help clear obstacles below you in approach. Seat pan was distracting, move back to glute area. Would like to see it with the audio footprint. The seat pan tactors were annoying. The tactors in the seat pan are in a bad location. Locating them farther back so that it hits the Gute muscle rather than more center and forward. The tactor location made me ignore everything else going on to make that one thing go away.
4	Would like to see tactile expanded and intesity adjusted with closeness. Prefer 20-30 ft out of rotor disk urgent, and 50-75 not as urgent. Seemed more distracting at the warning level due to imminent contact. Already aware of the danger with other cues.
5	Happy with how tactile layering was approached with the 3 layers. Sink rate tactors were very helpful. Not distracting.
6	Direction and distance were good. Sometimes distracting; at a hover, I would rather have the tactile rather than the audio. Audio enroute.
7	Normal trials the tactile cueing was appropriate. The last trial with my adjusted parameters the

Pilot	Comments
	tacticle cueing was too frequent. Visual, aural and tacticle parameters should be able to be adjusted independently so that I can get visual cues early, and tactile cues later. It gets my attention, which I like. The parameters need to be adjustable as stated above to avoid being distracting. All aircraft should be standardized, so different crew mixes will always be familiar with the distance range.
8	Tactile cueing was useful in the enroute phacse for altitde clearance and again on the approach/landing phase however with all different cueing systems active I did find that while I could feel the tactile cueing I sometime failed to process it as quickly if at all with most of my cognitive function going to the other cues. Kind of ignored tactile. Felt like it was redundant. With all of the symbology coupled with the visual and audio cuing I noticed at times that even though I could percieve the tactile cueing system activating I really didn't have the time to process that information especially during the approach phase.
9	Good. On approach it buzzed too much. More useful during in-route phase and less useful during landing phase.
10*	Useful, but unclear on what the signal meant. Task saturated. Did provide cueing to the area of interest. Seat pan was very useful for excessive sink rates.
11†	Wanted the ability to turn TSAS off due to too many cues being provided to the point of being a distraction.

Note. *Pavehawk †AH-64

Table D11. **Observer Notes, AAR and Survey Comments on ICE Cueing**

Pilot	Comments
1	Why is the horizon line white on PMD and green on HMD? It is difficult to follow route since you can see chevrons through the buildings. Not sure whether you turn before or after building. Maybe a fix…..(suggested by Rolf) Dominoes effect and don't draw as many that far out. Or have the further ones more faded to denote distance. looking at the ground, it gets a little confusing when the chevrons overlap, especially when you are going into a turn. Horizon line wasn't that useful at the time. I would like the collective indicator a little bit further out. Magenta arrows for route is great. Overall, it is a better page to navigate from and control flight. Not a fan of climb and descent tape. I like what we have now. Maybe making the tape larger. I do like the torque tape. Biggest complaint is the chevrons and their lack of ability to distinquish a route if it is going through obstacles. HAT page gives you a lot of feedback, but it doens't take into account any obstacles. Great rate of descent, but will take you right into an obstacle. I'd like more practice. I think it is better than what we have now. Allow for the flight path indicator to carry the same information as the clearance line.
3	White symbology on FLIR is hard to see. Heavy focus on velocity vector, ignoring other cues. Working on scan pattern. Pilot commented on excessive audio cues of vertical speed excessive. Likes altitude call-outs. Would like to see total distance or total time for route in top right corner (ICE). Velocity vector helps to reduce drift. Difficult to determine the route cues in relation to obstacles. Looking for pitch changes on takeoff. White symbology is tough to see on white IR picture. HAL is hard to see + or - in white out. Really liked the flight path marker. White symbology is hard to see on the IR picture. Would like enroute call outs for altitude for lower obstacle environment. Hard to see white cues in FLIR. UH-60 collective cues are a little different than the current implementation. Somewhat hard to change over. In the current HUD system for the ANVIS we have a way of selecting cues that we want to view. Having a way to select which cues are being displayed at which time would help reduce some of the confusion.
4	Powerlines blend with green horizon line. May need to overlay over heading line. In AH-64 velocity vector "diamond" placement can show landing point. Compared to difficulty to scan for ball/cup and collective cue. Colors seem to blend together. Would like some declutter ability. ICE - AH-64E velocity vector to the point. Difficult to scan with cup and ball and see obstacles. Horizon line may be better a ghost line like NVG's, rather than taking up so much display. Interferes with wires right now. ICE symbology didn't seem to guide appropriately (cup) had pilot at a hover after pulling up near building. Seemed that the algorithm got confused. Difficult to tell what attitude the A/C is at compared to the horizon line. The +/- 10 lines aren't fine enough resolution using PMD. Wires seem to be second priority to horizon line. Would like to see them in front. They are obscured. Main concern was with the wires not taking priority. Without HMD hard to tell in a bank what's going on. A predictive cone may be good. Moving FLIR sensor would be good to clear an area. Pitch attitude was very difficult to discern on takeoff. Would like airspeed to be better located on approach phase. The enroute portion was good. Still no situational awareness to what is to your left and right but good. The approach phase was cluttered and did not pick up obstacles between me and the LZ until to late.

5	Space between cyclic and collective cues are too far apart. HMD Condition: Difficult to see Humvees, symbology also covered them up. Good with colors. Take off and landing was good. Needed some getting used to. Distance between cueing was still a concern, but got better as it went on. Speed guidance mode was helpful with airspeed notification. Came in a little higher on approach, ground indicator seemed to come up a bit early, not very useful. ICE - CPT WALKER - *White out sensor, difficult to tell with symbology direction of nose. "Red Arrows could help to point in the ground direction." During the landing sequence, the cyclic and the collective cueing could be closer to one another rather than having them at their current settings, causing the pilot to have to overcompensate with his scanning.
6	Power line gets lost in the horizon line. The hardest thing to do is chase the cyclic. It also doesn't take into account what is in front of you. If you follow it blindly, it will take you right into something. Collective indicator could be a little more intuitive. The brown and green are confusing. Hover page didn't care for; Would like more distictive pitch indicator. Enroute was fine. Would prefer all data in one location. GS and ALT, for example. White on white is hard to see. The scale of the VSI indications scale should be larger increments to be consistent with real platforms (from 0-3000) in stead of 0-3000). Didn't care about speed bar. Approach guidance makes it look like there is a clear path. Cant follow angle with obstaclees in path. Improve symbology on ICE to replicate more intuative displays, like our current aircraft displays, audio tones are too overwhelming at times, the approach symbology on the ICE can give you a false sense of a clear approach path to the landing site. Recommend moving aircraft symbology (altitude, airspeed, radar altimeter, TQ) closer together. Also would like to have a more visable attitude indicator for pitch indications.
7	Put the symbology for velocity vector and collective cue closer together. Too far to scan. Still kinda of difficult getting used to the scale for the vertical speed. I'm used to a different scale. For speed guidance, I was going a bit too slow but as soon as hover page came on, it went to me going a bit too fast. In the actual aircraft performing an ILS provides symbology to keep the aircraft on an approach angle and approach course, similar to what the "cup and ball" and vertical speed guidance is providing. What the aircraft currently provides for an ILS is more intuitive than what was in the sim today. There was an issue with GS at about a 2 but the home plate already being past aircraft. I want to know my pitch attitude. It is hard to find. I want the pitch ladder to follow my head. Is the pitch ladder slaved to heading or track (track,he thinks, maybe it is heading). If there is a cross wind, that might mess with it if it is heading and I wouldn't like that. Following over water or desert, is ther the ability to have a grid system to give me a visual of where I am. It would also help with determining airspeed, altitude, motion paralax. Not a big fan of the speed tape on the fligt path marker. I like being able to move my head and scan. I found myslef looking down to go from the cup and ball and landing zone so I don't have to move my eyes as much to scan. Don't see me using heading numbers on horizon line, but if there was a beacon point for my LZ on the horizon line and a number for distance to LZ would be cool. Would like the alttitude audio call outs every 20s or so. Not as visual, too much visual already. Would there be a way to determine what is causing the flight path marker to turn yellow or red. Maybe a line to the obstacle that is going to collide with. Purple chevrons indicating route were too large. Smaller chevrons or more see-through would make them less distracting. Airspeed indicator on flight patch marker not intuitive. I would constantly have to think about what it was trying to tell me, rather than just reacting. Vertical speed indicator scale was confusing at the beginning, but became less of a problem later in the study. A "beacon" showing where my final point is in the flight plan, visable from any distance away, with an associated distance would increase situational awareness along the route. Pitch attitude needs to be more prominent in both the PMD and the HMD. HMD pitch information needs to follow where my head is looking.

8	HMD: Having a hard time reading ground speed. It is getting washed out. I can see the ALTs just fine, but not ground speed. I feel like it might be a glare with the HMD. With everything in black and white contrast, it is hard to distinguish the information on the screen over the FLIR image. Would like to have Distance readout in Kilometers to be under ground speed and a bit bigger. Need to have a distance display in KM below the airspeed readouts during the approach phase. The path chevrons need to be adjusted somehow to show terrain/obstacles such as buildings. Figure out way to show where the path goes without it going through the bldgs. Maybe they are blue if they are behind terrain or bldgs. Sometimes it was difficult to know where to go when you could view the path through obstacles and terrain. Initially didn't like the FPI but once I flew figured out how to use it, I ended up liking it. Don't have symbology white. Having white over white and gray FLIR is bad. make it all magenta. Vertical speed tape or (VSI) needs a digital readout of decsent or climb.
9	The vertical speed tape scale is disorienting - looks like you are ascending or descending more than you are. Crashed on second approach at the very end - "when it goes over to the hover page the last 20 seconds I get confused". "the last cue - I'm not picking that up very well" talking about hover page. "I just kinda completely focused on the cup and ball and didn't look at my altitude". "it's hard to tell forward speed" on approach. It's hard to tell what side of the building the path is on. "I feel like I got backwards on the yellow above and below on the flight path marker". Scale of vertical speed tape is different than the one they usually have. "Some obstacles came up so fast it was pointless". some of the stuff can be too much, especialy the landing ith the cup and ball, collective, etc. "what do I ignore?". I don't know which way to go. I thought I was going right of the building. Can't tell if cevrons are in front of or behind buildings. Is there any way to get rid of the heading - a little much. Liked the digital readout of torque. Did not like the reference indicator for earth.
10[*]	Depiction of the approach path caused some spatial disorientation, when it showed up in the turn. Flying mainly off of the image. It's difficult to fly off just the "raw cueing" when sensor degrades. In AH-64 velocity vector "diamond" placement can show landing point. Compared to difficulty to scan for ball/cup and collective cue. Enroute - liked the flight path marker. Heavily reliant on flight path marker, under HMD, without the FPM experienced spatial disorientation. Approach - FPM speed tape was opposite of the H-60, and caused some confusion. Landing - good symbology, but needs to consider obstacles on final approach. The horizon line should be all the way across the PMD. Using the flight path marker and the horizon helps to maintain orientation.
11[†]	Have true airspeed above ground speed. Pitch ladder should move with your head.

Note. [*]Pavehawk [†]AH-64

Table D12. **Observer Notes, AAR and Survey Comments on San Francisco Database.**

Pilot	Comments
1	No comments.
3	No comments.
4	No comments.
5	No comments.
6	HMD: Hard to see HMWWV's on pad….sensor model issue. Can they be lightened? Demo1 HMD: Helicopters on pad need to be lighter here also.
7	No comments.
8	The aircraft (Chinooks) on taxi blend into flight line pretty well. Hard to see until you are right on top of them.
9	No comments.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D13. **Combined Observer Notes, AAR and Survey Comments on Simulator.**

Pilot	Comments
1	No comments.
3	No comments.
4	No comments.
5	No comments.
6	No comments.
7	No comments.
8	When you are in a hover, it seems like the inputs you make are very sensitive. When you are in forward flight, it seems like you need to make bigger inputs to get it to do what you want.
9	Sim counted a collision with no apparent obstacle. Good. No issues.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D14. **Combined Observer Notes, AAR and Survey Comments on Mission Scenarios.**

Pilot	Comments
1	Having more of a challenging taxi phase would be a good idea. That one (baseline condition) felt like it was the easist one yet. The alerts sometimes make you feel like you have to navigate away from it. Maybe just have a less harsh alert. Add more obstacles during taxi. Routes were fun. Couple of the pad landings were tough. It really makes you use the system.
3	Use IIMC scenario to test more pieces. No significant changes. Would like to see an IIMC scenario "cloud" insertion.
4	Scud layer effective in keeping low. Appropriate for what we were doing.
5	Urban enivronment was tough to navigate. Appropriate.
6	No comments.
7	Great route selection to show capability. Develop vignettes to develop transition between VMC and IMC (ICE and cueing) …brownout, inadvertant IMC
8	Thought the vignettes were really well done. A mix of challenging and fun.
9	Couldn't see the vehicles in the hover/taxi phase. Good. On some it was hard to tell where you were supposed to go - chevrons went through buildings and obstacles.
10*	Scud layer effective in keeping low. Working on scan. Trial 5: 4C (V+T PMD)Felt like this was the best combination. There are a lot of other operational tasks that we have to do that I would have to abandon. I don't have enough SA to attend to other aspects. My workload was less on this one. I felt like I could communicate if I needed to. More experience (5-10) hours additional flight time would help with this. Good.
11†	UH-60A last flight about 20 years ago. UH-60M last flight about 2 years ago. Remembered enough to fly for event. Had opportunity to read-ahead on system and symbology.

Note. *Pavehawk †AH-64

Table D15. **Combined Observer Notes, AAR and Survey Comments on Training.**

Pilot	Comments
1	Does the speed tape tell you what rate your ascending or descend? NO…That is going to be hard….should have that. Good for classroom and simulator training. Being able to ask questions was great. Put clearance line on a slide in training so I know what it is before demo. Incorporate Horizon obstacle avoidance line in slides.
3	Would like training with measurement area that shows distance with helicopter relation to cueing set up. Maintain minimal classroom, focus on hands on training. The only way to become more proficient would be to practice. Short of getting an entire day of training in the simulator I do not see a good way to become more proficient.
4	Good.
5	No significant comments. Good.
6	Very throuough; adequate for both classroom and SIM. Feeling comfortable flying with equipment this different would require hours of familiarization, unrealistic for this study.
7	Classroom: No issues. SIM: Few restarts needed, but no real issues.
8	Has there been thought as to how this will be used in a combat environment with radar signature? We are being told now to turn systems off that would have radar signatures. Thought all classroom training and sim training was well done and time appropriate
9	Useful and enough information. Take a couple min to point out the symbology in aircraft instead of on paper.
10*	Good.
11†	No comments.

Note. *Pavehawk †AH-64

Table D16. **Combined Observer Notes, AAR and Survey Comments on Biometric Gear.**

Pilot	Comments
1	Due to EEG issue, Trial 5 using HMD was completed on Day 2. It is uncomfortable, but it isn't that bad. Allow each participant try their own helmet and then another one that is one size larger and see which one they like.
3	Slight headache.
4	Good.
5	Good.
6	EEG with a helmet was not comfortable. Rest of everything was good.
7	Head gear uncomfortable with helmet, but okay in short periods.
8	May need to use a tactile belt in place when fitting EEG leads so that there is less chance of belt interfering with EEG placement.
9	Not bothersome.
10*	N/A
11†	N/A

Note. *Pavehawk †AH-64

Table D17. **Combined Observer Notes, AAR and Survey Comments on Eye Tracker.**

Pilot	Comments
1	Wearing the HMD, I didn't see it at all. Using the PMD, I was focused on screens so it didn't bother me.
3	Good. No issues.
4	Good.
5	Good.
6	No issues.
7	Not distracting.
8	Did not notice it being there.
9	Forgot it was there. MFD is more functional.
10*	N/A
11†	N/A

Note. *Pavehawk †AH-64

Table D18. **Observer Notes, AAR and Survey Comments on Workload Questionnaires.**

Pilot	Comments
1	I wasn't manageing any other task other than flying as far as workload. The symbology was increasing my workload based on my unfamilarity with it all.
3	No comments.
4	HMD V+A+T: Lower workload enroute. Higher workload on approaches and landings.
5	Not task saturated in general.
6	HMD V+A+T: How did I get through those two cranes??? I looked away for just a second and they were just right there. HMD Baseline: Wires: I didn't see them at all…they just kind of popped out of no where. It caused me to scan a lot more…my approach was better besides the powerline because I didn't have all that other stuff.
7	No comments.
8	I am getting a little fixated trying to figure out what to process.
9	No comments.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D19. **Observer Notes, AAR and Survey Comments on Usability Questionnaires.**

Pilot	Comments
1	Not too cluttered maybe there was some things I didn't use, I guess. No usability issues.
3	No comments.
4	No comments.
5	Would be operationally useful. Symbology was good after getting used to it.
6	No comments.
7	No comments.
8	No comments.
9	No comments.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D20. **Observer Notes, AAR and Survey Comments on Trust in Automation Questionnaires.**

Pilot	Comments
1	spatial audio would sometimes blend together.
3	The tactors in the seat pan are in a bad location. Locating them farther back so that it hits the Gute muscle rather than more center and forward. The tactor location made me ignore everything else going on to make that one thing go away.
4	No comments.
5	No comments.
6	The visual cueing during the approach phase appears to give you a clear path to intended point of landing. Many times there were obstacles between the aircraft and the landing site that were not depicted.
7	I rely on visual cueing more than other senses, so I would like more predictability in order to have more confidence in the system.
8	for audio and visual systems there were a number of time that hazards would show up as the aircraft was passing or when directly below the aircraft especially when those hazards were colocated with rising terrain.
9	No comments.
10*	No comments.
11†	Visual 360 SA Cueing was not 100% reliable at detecting some tower/crane obstacles until almost too late. Once I realized that not all hazards were being detected, scan and workload actually increased

Note. *Pavehawk †AH-64

Table D21. **Observer Notes, AAR and Survey Comments on Motion Sickness Questionnaires.**

Pilot	Comments
1	I little bit of motion sickness.
3	No comments.
4	No comments.
5	No comments.
6	No comments.
7	No comments.
8	No comments.
9	No comments.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D22. **Observer Notes, AAR and Survey Comments on Overall Questionnaires.**

Pilot	Comments
1	Wording needs to be more pilot speak instead of engineering speak. [We corrected this after S1]
3	No significant comments.
4	No comments.
5	OK
6	Clear and concise
7	No comments.
8	Quick and to the point. Some information it hard to quantify on a scale and is best passed on through verbal interview.
9	The surveys after each run were okay. The surveys at the end were a little difficult because some things were hard to remember.
10*	Good.
11†	No comments.

Note. *Pavehawk †AH-64

Table D23. **Observer Notes, AAR and Survey Comments on Clearance Line.**

Pilot	Comments
1	Didn't use conformal line during demo at all. Kind of meshed with horizon line and wires. The color red of the clearance line and the color red of the wires meshed together. I could see it being more useful in city areas. Information could be wrapped up into flight path vector. It was just added clutter. In a mountain range area, it might be benefical. Not that accurate in an urban environment. Capability to turn on or turn off with one button might be ok. Changing colors to indicate that a current flight path would impact obstacles. Clearance line did not seem reliable. I would see benefits in current environment (desert/mountain range) but not urban environment. Suggestion to allow this feature to be turned on and off. V & A & T & CL HMD - The clearance line did not offer any additional useable information. The line meshed with power lines at one point and was difficult to differenciate between the two. V & A & T & CL PMD - Obstacle avoidance horizon line offered little value with SA.
3	Possibly useful, put the flight path indicator above it and it's good to know. No excessive clutter. Need more time on it. In the two vignettes that I flew I was not able to really test the system. I think a more exhaustive look at the terrain line is necessary for me to give it a real assesment.
4	Maybe drop the clearance line in approach to highlight obstacles. Clearance line was good on approach, that sensor may miss. V & A & T & CL HMD - THE HORIZON LINE IS GOOD SITUATIONAL AWARENESS AND SO IS THE GREEN LINE HITH HEADING BUT WIRE OBSTACLES AND OTHER THINGS BLEND IN TO THEM. COLOR SCHEME IS GOING TO BE IMPORTANT AND RED WIRES WITH A RED HORIZON BLEND IN AND THE RED AND GREEN TOGETHER IS A BAD COMBO.
5	Red line was not very useful. Clearance line was not used much. Prefer 2D UH-60M color

Pilot	Comments
	banding for altitudes over terrain. Fairly easy. Cueing worked well. Able to use, but not very useful.
6	Contour line was something new. Didn't really care about it for urban envorments. It gets lost. Maybe in rural enviornments it might be more beneficial. I'm not sure it provides much benefit in urban terrain, but would be useful in mountains with limited visability.
7	For how low I'm flying I feel like it is looking to far out. Now with this terrain, it is helpful. When the red line outlined that tower, I felt like it made it look farther away then it was. It gets kind of busy with that red clearance line on there. I thought I was going to like it more than I do. I don't know how to use that information. It's hard to tell what it is trying to warn me about. It draws my attention but really its not the most relevant obstacle but yet it is taking my attention. Maybe if you could toggle it off and on. It's not drawing my attention to what I need to be focused on at the time. Clearance line was to me just more clutter. It would rarely show the most urgent hazard, but would draw my attention to an arbitrary line of hazards. Hazards outlined by the clearance line were hard to judge how far away they were, sometimes appearing further out than they actually were. V & A & T & CL PMD - Clearance line appeared to make obstacles look further away than they really were. V & A & T & CL HMD - Clearance line draws my attention away from other obstacles when the clearance line may not be showing me the highest priority obstacle.
8	Did not like the clearance line. Honestly did use it at all to the point where I did not notice it once flying.
9	Nice and nice to have separate from earth ref line. Would be nice during terrain vs urban environment. V & A & T & CL PMD - Red clearance line limit was helpful at some points. Sometimes the red line and also audio cues at the same time became to much.
10*	Better SA, due to familiarity. The red line was not beneficial at all. Not useful.
11†	Some tower obstacles were detected by the system late or not at all, requiring heightened concentration and accelerated visual scanning. Eyes getting a workout.

Note. *Pavehawk †AH-64

Table D24. **Observer Notes, AAR and Survey Comments on HMD.**

Pilot	Comments
1	I am definitely loosing my depth perception with these. the right side is a little blurry in the HMD…which may cause the motion sickness. HMD: left and right eyes were a bit off…blury which may be why I got a bit of motion sickness, plus helmet was tight. Normally wear a medium, but might try large with the other stuff under it. Eyes were the same. One (Right eye) was blurry making it uncomfortable causing sickness. I do prefer HMD over PMD. It provides more SA. You need more training on it though. Vibrations of the sim shook my HMD coming into landing. Might have been the seat shaker causing it. Could have reverted to PMD at that point, but didn't think about it. The only information that the HMD didn't have was the route, so I did look at the ICAD for that. HMD gave more SA with the environment and could be very advantageous in DVE with sufficient training.
3	Somewhat disorienting. Some occlusion on the corners (blue color). The workload would reduce with more training. Still getting used to the HMD to look "through a/c". Technology was somewhat lacking, difficult to focus it. Likes the idea of a visor implementation. The adjustments were too gross. Would need fine tuning. Clearance line in HMD was mostly ignored due to tiredness. I think the technology on the HMD has not caught up to the rest of the system. Being able to project the image on to the visor of the helmet would create less eye strain. I was unable to ever get the ENTIRE image focused and had a lot of eye strain.
4	Magenta colors blend over the flight path. HMD scan pattern is difficult for approach. Scan pattern: Easier to get side to side SA, PMD is hard to get for side to side. Somewhat strange feeling with head movements and seeing through the A/C. Liked the HMD enroute not approach/inbound due to scan pattern. Would like to quick switch it off if necessary on approaches.
5	In HMD, Spatial Awareness is really good. Good, no serious issues. Liked the scan ability and able to see thru a/c and turns. Heading line was fine, but not attended much. The HMD provides peripheral vision, which is key to flying around obstacles.
6	Note from observation is that some participants have the HMD lens about an inch from their eyes and some have it much closer to eye. Left eye focus is blurry. Participant attempting to adjust lens distance to correct. Bringing it closer to eye. Either trim ball is blurry or everything else is blurry. Adjusted so that evereything else is clear and trim ball is a bit blurry. I couldn't really get the HMD as clear as I wanted. I could see it good enough, but wish it was better. Colors were fine. It was just the white on white. Clarity: 7 out of 10. either top or bottom was clear; comfortable, no eye strain. The HMD was too much to look at. Although it gave more situational awareness, it would degrade my ability to fly usuing actual outside references if VMC. The PMD is adaquate for use as a contingency if DVE is.
7	Pitch ladder on the hover page ?? (pitch information very difficult to determine using HMD with hover info displayed). No pitch ladder during hover phase. Digital pitch readout(slaved to horizon) was on PMD in hover but not the HMD or at least you didn't see it. Left eye seemed to be less in focus than the right eye. It was heavy, causing bad hot-spots along my forehead. The HMD was too much to look at. Although it gave more situational awareness, it would degrade my ability to fly usuing actual outside references if VMC.
8	HMD has a bit of a lag, jumping. Jumping is getting worse as this first trial progresses. Every 5 seconds or so. It is starting to hurt in the forehead. Was comfortable to wear and once adjusted and was clear. Said that maybe would prefer the HMD after more use because you can turn your head and see things.

Pilot	Comments
9	Terrible. Comfort wasn't bad. The movement was terrible - too much. The HMD is very diffuclt to fly with. The head movement is very overwhelming when on approach and during large turns.
10*	Feels like an overwhelming amount of data. Oversaturating my cross-check. Checking PMD under the HMD, due to comfort. I like the wire overlay on the HMD a lot. Enroute is very good. In hover/take-off/landing, it's difficult due to everything moving when I move my head. Got spatial disorientation when the flight path marker went away, and handed off controls. I like using this for flying patterns and enroute, but I prefer to transition to heads down for approach. The cross-check is more difficult with the HMD. Lots of data to process at the beginning. Got more comfortable. Prefer PMD over HMD. Liked the HMD for enroute to see turns. This system is effective for DVE pilotage.
11†	heads-out is always better than heads-down when on the flight controls.

Note. *Pavehawk †AH-64

Table D25. **Observer Notes, AAR and Survey Comments on PMD.**

Pilot	Comments	
1	During landing phase, PMD went black similar to night flight for 2 seconds. PMD was easier to fly without training.	HMD
3	No comments.	PMD
4	Difficult to determine depth compared to HMD. Got used to it. Felt like approach was easier with PMD due to symbols being closer. PMD scan pattern in approach is still difficult to find obstacles. Scan pattern: Easier to get side to side SA on HMD, PMD is hard to get for side to side. I prefer the PMD only because of the HMD causing me to feel motion sick and spatial D.	PMD
5	PMD: Fixated on wire symbology and didn't correct. Crashed into wires. Occasionally looking down to PMD under HMD. Prefered the PMD. Althought both have pro's and con's, I prefer the PMD primarily due to the fact that, that information allows my mind to process information at a noral rate. As oppsed to wearing the HMD, where it seems as if the same information is projected a lot quicker resulting in inadvertant control movements.	PMD
6	This is tough without peripheral vision.	HMD
7	The PMD is adaquate for use as a contingency if DVE is encountered.	PMD
8	Flew better off of the PMD. Enjoyed PMD better. It was clearer. Also was 2d day and might be effected by training effects.	PMD
9	Clarity on MFD liked better. I found the PMD to be much easier to fly with and control. The cues on the HMD were difficult to follow with any aircraft vibrations.	PMD
10*	Prefer the horizon line to run all the way across the PMD. Hard to interpolate where the flight path marker is (in relation to the horizon) if it's on the edges. I'm biased due to the fact im a HH-60G Pavehawk pilot with a PMD	PMD
11†	Discussed concerns of the actualy clarity the PMD visuals would have in DVE, believes PMD would look more like it does in the smog layer (over 100 feet)	HMD

Note. *Pavehawk †AH-64

Table D26. **Observer Notes, AAR and Survey Comments on ThreatTune.**

Pilot	Comments
1	The abiity to pause the simulation would be a benefit.
3	Post: Make slightly wider and further out. Open cone to square ending to not get caught up too late.
4	Pre: Minor changes to width and base. Post: Would like an airspeed cue for deviations, not on the wing of the flight path marker. Difficult to know attitude without a horizon line. Would like to know in turns what's on the sides. Prefers a wider width for the cone. May like to enlarge the warning zone at hover/6kts. That ability does not seem to be adjustable. Would be good for hover/taxi. Would like ability to adjust FLIR (to look around A/C) at LZ PZ. The wider base was too cluttered. Went with 10s caution, default cone.
5	Pre: Minor changes to TTC. Post: Leave powerlines default. Very good. Increase caution time to 8 seconds. Increase warning time to 5 seconds. Default for the overall width. Slightly wider base for the default. Default TTC transition. Can be overwheliming with cues, but more advantageous than not having it. Thought that the refinements were better during the record route. Liked the earlier indications modifications done in threat tune post threattune.
6	No comments.
7	No comments.
8	Post: I like that it is a little narrower but the warning a bit sooner. I pretty happy with this now. It is nice that as you pass it, it disappears too. In a hover, I don't feel like I need 75 feet around me for the caution zone. During Flight: This is much better. That was a lot better, I think. At a hover, make threat rings adjustable for pilots for each mission. And have the ability to turn off and on. Would only use in DVE.
9	No comments.
10*	No comments.
11†	No comments.

Note. *Pavehawk †AH-64

Table D27. **Observer Notes, AAR and Survey Comments on General Items.**

Pilot	Comments
1	Fully relaying on the system makes you use the system. Good to isolate technology.
3	Likes extra cueing compared to baseline. Not comfortable in helmet. Feeling eyestrain. Feeling more comfortable with the overall system.
4	Having trouble with pedals due to height. Working on scan. Very difficult to see obstacles in baseline.
5	Likes the symbology overall. Would be operationally useful. Difficult to hear commands over ATC chatter. Bumped a part of the ship. Cueing worked, but FPM was red. ATC Clutter is still distracting. Symbology was good after getting used to it. Baseline was difficult when the cues were taken away. Participant sometimes deviates from flight path in very heavy areas that require between buildings. The ability to adjust the warning and caution distances to obstructions is very instrumental to aviators.
6	No comments.
7	HMD: Not sure about all the symbology and what sticks with my head. Some sort of counter weight on the helmet might help out. I've got a pretty good hot spot on the front. Visual + auditory + tactile gave the best situational awareness, but at times was too much. Auditory became distracting with too many hazards. After initial notification of a hazard with the auditory, it could be handed off to tactile. That would free up the "noise" in the aircraft for radios or ICS communications. Hand-off from auditory to tactile. More different colors for visual cueing (orange and red hard to tell apart). More cueing for hazards below you in the enroute portion. 30 feet not far enough below the aircraft.
8	For audio and visual systems there were a number of time that hazards would show up as the aircraft was passing or when directly below the aircraft especially when those hazards were colocated with rising terrain.
9	Having a way to turn some of the cueing on and off would be good. doesn't really like the symbology. can't keep head still on the approach. Hard to see at landing. Was on top of it before he knew it and couldn't make a correction. Pulling on the front of his helmet. rubbing his head and in between his eyes. Maybe on first couple of scenarios, do not have ceiling.
10*	Pilot is used to pilotage with FLIR. Needs to move predictively. Sterile cockpit, there would not be much talking. That being said, at some critical phases of the mission, the constant bombardment of audio and tactile cues was annoying. If something needed to be discussed between crewmembers, the message may not be received.
11†	Worried about Radar Theory. How strong is the radar? Too strong and we will be a beacon for the enemy. Can we turn if on and off? Would prefer that ability. Pilot states still getting used to blackhawk flight verse apache. Had an issue viewing altitude and airspeed at the same time, and which to prioritize.

Note. *Pavehawk †AH-64

Table D28. **Observer Notes, AAR and Survey Comments on Improvements.**

Pilot	Comments
1	smaller threat detection circle. Improve threat page to show more valuable information. Allow for adjustments for detection and alert to be pilot dependant.
3	In the current HUD system for the ANVIS we have a way of selecting cues that we want to view. Having a way to select which cues are being displayed at which time would help reduce some of the confusion.
4	No comments.
5	1. The ability to adjust the warning and caution distances to obstructions is very instrumental to aviators. 2. During the landing sequence, the cyclic and the collective cueing could be closer to one another rather than having them at their current settings, causing the pilot to have to overcompensate with his scanning.
6	Improve symbology on ICE to replicate more intuative displays, like our current aircraft displays, audio tones are too overwhelming at times, the approach symbology on the ICE can give you a false sense of a clear approach path to the landing site.
7	Hand-off from auditory to tactile. More different colors for visual cueing (orange and red hard to tell apart). More cueing for hazards below you in the enroute portion. 30 feet not far enough below the aircraft.
8	There needs to be a way to mute the audio for the wires or at least dim the volume. The detection space around the aircraft at a hover needs to be made smaller or at least adjustable. Make initial volume for wires loud then after a second or two reduce sound.
9	I think being able to select or adjust the warnings you get or being able to turn them on and off individually would be great. The tactile belt would be nice to have less sensitivity or more distinguishable vibrations. I did like the TQ display on the HMD better than the PMD, it helped removing the bar to make it less cluttered.
10*	No comments.
11†	Visual detection -only- sooner. Auditory and Tactile cue defaults seemed to work well in the given mission set parameters. Earlier visual representation would heighten SA without being a distraction or SA distractor.

Note. *Pavehawk †AH-64

Table D29. **Observer Notes, AAR and Survey Comments on TTPs.**

Pilot	Comments
1	No comments.
3	Would like to use the system even in clear environments to augment spatially where objects are. Very tiring, lots of focus required for these scenarios; may reduce operational time. Gives the ability for flying in a high obstacle environment, but not advisable for long periods.
4	EGI data for LZ may be inaccurate. Need color coding for accuracy of LZ data. Should be able to "drop" LZ if necessary.
5	Whole system would be good with MEDEVAC and hoist missions in brown/white out. Sink rate tactors would also be good for these missions. Sometimes altitude can drop quickly. MEDEVAC, Brown out and White out during air assault would be good to have, could land multiple A/C in an LZ. Helpful for an urban environment. Could be useful for multi-ship environment.
6	No comments.
7	No comments.
8	No comments.
9	No comments.
10*	FLIR with velocity vector (mathematic) approaches with cueing will get the a/c down effectively.
11†	No comments.

Note. *Pavehawk †AH-64

Table D30. **Pilot Comments on Workload on PMD**

Pilot	Cueing Configuration	Comments
1	**Baseline**	Relied more on pilotage skills to navigate course rather than the need to manipulate controls constantly to avoid obstacles. When using obstacle avoidance technology, I attribute an increase in workload to a 'reaction' style response that requires a quick change in mission profile to avoid obstacles.
	Visual	Workload increases slightly with only visual cues.
	Visual + Auditory	More familiar with MFD as primary reference.
	Visual + Tactile	As I become more familiar with the system, workload is beginning to depend on the route difficulty and not necessarily the obstacle avoidance technology.
	Visual + Auditory + Tactile	Workload is becoming reduced as familiarity with system increases.
4	**Baseline**	No comments.
	Visual	No comments.
	Visual + Auditory	No comments.
	Visual + Tactile	Everything was a 4 until landing phase. The lack of motion parallax with visual cues makes speed hard to determine. Overworked speed and forgot about altitude.
	Visual + Auditory + Tactile	On approach the lack of awareness from chasing the cup and ball and TQ setting overwhelms pilots and lose sense of obstacles and LZ. Made some task difficult.
7	**Baseline**	No comments.
	Visual	No comments.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	A lot of attention was given in the scenario to identify what the different cues were telling me.
8	**Baseline**	No comments.
	Visual	wires much harder to anticipate without audio
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.

Pilot	Cueing Configuration	Comments
9	**Baseline**	relied much more on cup and ball indicator on this scenario. The visual and audio indicators on the wires would have been nice, a few sets were not seen until the last second.
	Visual	After scanning more to the cup and ball and using the collective position indicator as a secondary indicator it was helpful during the approach. Once short final after transitioning to visual the cup and ball indicator began to get off. Hard to focus outside and use the indicators short final
	Visual + Auditory	Some obstacles are recognized to late or when there are quick changes in terrain and can cause an unnecessary alert when flying on the route
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.
11†	**Baseline**	No comments.
	Visual	No comments.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	Overwhelming during landing. Could have used a silencer for last few seconds.

Note. *Pavehawk †AH-64 2) Pilots 3, 5, 6, and 10 had no additional comments for these categories and thus are excluded from the table.

Table D31. **Pilot Comments on Workload on HMD.**

Pilot	Cueing Configuration	Comments
1	**Baseline**	Was able to focus more on the symbology and obstacle avoidance resulting in greater attention divoted to maintaining mission profile.
	Visual	Wasn't managing any other tasks other than flying. The symbology is increasing workload based on unfamiliarity.
	Visual + Auditory	Familiarity with the system is starting to decrease workload.
	Visual + Tactile	Focus was directed towards symbology and deviating from obstacles; somewhat difficult to maintain aircraft control.
	Visual + Auditory + Tactile	No comments.
3	**Baseline**	No comments.
	Visual	No comments.
	Visual + Auditory	No comments.
	Visual + Tactile	I feel like the workload would be less with more training time and experience.
	Visual + Auditory + Tactile	No comments.
4	**Baseline**	WITHOUT ANY AUDIO AND VISUAL I COULD NOT MAKE OUT A MAJORITY OF THE WIRES OR OBSTACLES
	Visual	No comments.
	Visual + Auditory	GOOD VISUAL CUES MADE IT EASIER TO NAVIGATE AND THE AUDIO WAS HELPFUL STILL A LOT GOING ON WITH A LOT OF SENSORY STIMULATION ON SHORT FINAL ALMOST MAKING IT DIFFICULT TO FOCUS ON THE LANDING

Pilot	Cueing Configuration	Comments
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	ENROUTE IS REDUCED WORKLOAD BUT APPROACH GATE INBOUND THE AMOUNT OF MOVEMENT FROM THE LZ TO THE BALL AND CUP/ COLLECTIVE POSITION INDICATOR IS EXCESSIVE. JUNIOR PILOTS WILL HAVE ISSUES WITH THE SCAN IF A 1500 HOUR PILOT IS AS WELL.
7	**Baseline**	No comments.
	Visual	When the flight path marker would turn yellow/red, an indication on the screen of what is causing that indication would help me to be aware of what exactly I would hit if I did nothing else
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.
9	**Baseline**	No comments.
	Visual	There was difficulty trying to see the LZ without being 100% on the cues to bring you in. There was a tower that I could not see until I was right on top of it
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	On short final there are way to many cues giving you commands it makes it very difficult to have a scan and actually brings down situational awareness with so many alarms going off at once

10*	**Baseline**	reduced audio input was doubled. Allowed for false sense of security but also reduced stimuli to pilot. Almost smacked wires due to no audio
	Visual	No comments.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	better SA on wires with audio
11†	**Baseline**	No comments.
	Visual	No comments.
	Visual + Auditory	No comments.
	Visual + Tactile	growing pains reduced by having familiarity with ah-64 hdu. Missing head tracker, continuous pitch reference, and rate of climb/descent symbology.
	Visual + Auditory + Tactile	No comments.

Note. *Pavehawk †AH-64 2 Pilots 5, 6, and 8 had no additional comments for these categories and thus are excluded from the table..

Table D32. **Pilot Comments on SA on PMD.**

Pilot	Cueing Configuration	Comments
1	**Baseline**	Tactile did not offer much advantage except during ground taxi and approach phase.
	Visual	Loss of audio reduces SA
	Visual + Auditory	Was unable to scan around the aircraft to determine obstacle location. Limited Field of View. I do feel that the fixed compass rose and attitude indicator on the PMD give a better reference to aircraft location.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.
3	**Baseline**	No comments.
	Visual	No comments.
	Visual + Auditory	Visually I had a hard time telling how high my HAT was as terrain varied.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.
4	**Baseline**	Situational awareness of obstacles especially wires was almost zero. Looking for obstacles over saturated me and had me abandon certain flight issues such as trim.
	Visual	The lack of audio and tactile seems to allow better focus on the approach but still hard to scan all information and focus on LZ and obstacles in between aircraft and obstacles.
	Visual + Auditory	No comments.
	Visual + Tactile	Without audio it took longer to see things as no other hints were given until the tactile kicked in last minute.
	Visual + Auditory + Tactile	No comments.

Pilot	Cueing Configuration	Comments
7	**Baseline**	No comments.
	Visual	When the flight path marker would turn yellow/red, an indication on the screen of what is causing that indication would help me to be aware of what exactly I would hit if I did nothing else.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.
9	**Baseline**	Relied much more on cup and ball indicator on this scenario. The visual and audio indicators on the wires would have been nice, a few sets were not seen until the last second.
	Visual	After scanning more to the cup and ball and using the collective position indicator as a secondary indicator it was helpful during the approach. Once short final after transitioning to visual the cup and ball indicator began to get off. Hard to focus outside and use the indicators short final.
	Visual + Auditory	Some obstacles are recognized to late or when there are quick changes in terrain and can cause an unnecessary alert when flying on the route.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.

Note. [*]Pavehawk [†]AH-64 2 Pilots 5, 6, 8, 10 and 11 had no additional comments for these categories and thus are excluded from the table.

Table D33. **Pilot Comments on SA on HMD.**

Pilot	Cueing Configuration	Comments
1	**Baseline**	Underflew wires. Could not see smaller obstacles without cueing.
	Visual	Some of the wire symbology was hard to see - more prominent, maybe a different color.
	Visual + Auditory	Relied more on visual cueing for SA. Audio alerts tended to bleed into one another not allowing for multiple hazards to be distinguished at one time.
	Visual + Tactile	Found tactile to be more helpful during hover taxi than forward flight.
	Visual + Auditory + Tactile	Tower on approach path was not identified until late. Wires were difficult to see at times; recommend different color or thicker line. Flight path was sometimes confusing to determine whether it went before or after a building. Recommend arrows come from the sky to the ground and are partially covered by obstacles.
3	**Baseline**	No comments.
	Visual	No comments.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	I forgot that I could look below the aircraft as I was descending during the approach to ensure that I was clear of obstacles.
4	**Baseline**	No comments.
	Visual	BUILDINGS IN APPROACH PATH WHERE HARD TO SEE WHILE WATCHING OTHER CUES.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.

7	**Baseline**	No comments.
	Visual	Wires much harder to anticipate without audio.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.
9	**Baseline**	No comments.
	Visual	There was difficulty trying to see the LZ without being 100% on the cues to bring you in. There was a tower that I could not see until I was right on top of it.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	On short final there are way to many cues giving you commands it makes it very difficult to have a scan and actually brings down situational awareness with so many alarms going off at once.

Note. *Pavehawk †AH-64 2 Pilots 5, 6, 7, 10 and 11 had no additional comments for these categories and thus are excluded from the table.

Table D34. **Pilot Comments on Usability on PMD.**

Pilot	Cueing Configuration	Comments
7	**Baseline**	Symbology would sometimes cover obstacles.
	Visual	No comments.
	Visual + Auditory	No comments.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.
9	**Baseline**	No comments.
	Visual	No comments.
	Visual + Auditory	Slight confusion on the airpseed indications on the flight path marker.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.

Note. *Pavehawk †AH-64 2 Pilots 1, 3, 4, 5, 6, 8, 10 and 11 had no additional comments for these categories and thus are excluded from the table.

Table D35. **Pilot Comments on Usability on HMD.**

Pilot	Cueing Configuration	Comments
1	**Baseline**	No comments.
	Visual	Some things I didn't use.
	Visual + Auditory	Route waypoint chevrons made it difficult to depict where the route started. This is mainly due to the ability to see the chevrons through bulidings. I was unsure if the route was over or behind the buildings.
	Visual + Tactile	No comments.
	Visual + Auditory + Tactile	No comments.
9	**Baseline**	
	Visual	
	Visual + Auditory	
	Visual + Tactile	
	Visual + Auditory + Tactile	

Note. *Pavehawk †AH-64 2 Pilots 3, 4, 5, 6, 7, 8, 10 and 11 had no additional comments for these categories and thus are excluded from the table.