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Integrated Cueing Environment: Simulation Event Four

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14. ABSTRACT
Eight Army aviators evaluated two sets of visual symbology in conjunction with current and advanced flight controls and two display types (helmet mounted and panel mounted). Flight performance, biometric measures, and subjective feedback were used to assess the usability and reduction in workload as well as changes in performance resulting from symbology, flight controls, and display used. Overall, the assessment found one symbology set to result in better performance and lowered workload (assessed biometrically and subjectively).

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Summary

An experiment was conducted to determine the efficacy of different types of multi-modal cueing to assist pilots during flight in degraded visual environment (DVE) conditions. Haptic and aural cueing, symbology displayed on either a helmet mounted display or panel mounted display, and advanced flight control laws for pilotage in DVE conditions were assessed. Eight pilots performed several flight tasks in a UH-60 Blackhawk simulator to evaluate the multi-modal cueing. The study was comparative in nature with pilots evaluating (1) a refined version of previous haptic, aural, and symbology cueing to an alternate version; (2) advanced flight control laws to UH-60 flight control laws; and (3) usability of symbology on a helmet-mounted display (HMD) compared to a panel-mounted display (PMD).

Objective measures were pilot performance and biometric response during flight tasks. Subjective measures were pilot ratings for workload, situational awareness (SA) and system usability. An additional workload and usability measure was eye tracking which provided data on visual gaze, fixation and pilot distraction.

Two sets of symbology were evaluated for visual cueing during flight in DVE. Symbology Set A provided a high level of cueing information to pilots, and Symbology Set B provided significantly less cueing symbology. Symbol Set A outperformed B in almost all phases of flight and in almost all metrics. Haptic and aural cues associated with Symbology Set A were significantly preferred by pilots compared to Set B.

Pilots preferred using the HMD compared to the PMD most of the time and commented that they had difficulty with the advanced control laws, although the advanced flight control laws produced superior performance during approach and hover flight tasks. Biometric data confirmed that pilots were working harder when using these advanced control laws. This may have been due to a lack of pilot experience using the advanced flight control laws prior to this test. The pilots reported that they became more confident in their use throughout the experiment. The table provides the overall statistically significant trends in this study.

Table. Overall Statistically Significant Trends

<table>
<tr><th></th><th>En-route</th><th>Approach</th><th>Hover</th><th>Landing</th></tr>
<tr><td rowspan="2">Performance</td><td rowspan="2">Set A was superior</td><td>Set A was superior</td><td>Set A was superior</td><td>Set A was superior</td></tr>
<tr><td>Advanced Flight Control Laws were superior</td><td>Advanced Flight Control Laws were superior</td><td>PMD was superior</td></tr>
<tr><td rowspan="3">Biometric</td><td>HMD was superior</td><td>UH-60 Flight Control Laws were superior</td><td>HMD was superior</td><td rowspan="3">----</td></tr>
<tr><td>Set A was superior</td><td>HMD was superior</td><td>UH-60 Flight Control Laws were superior</td></tr>
<tr><td>----</td><td>Set A was superior</td><td></td></tr>
<tr><td>Subjective Workload</td><td>Set A was superior</td><td>Set A was superior</td><td>Set A was superior</td><td>Set A was superior</td></tr>
<tr><td>Subjective SA</td><td>----</td><td>Set A was superior</td><td>Set A was superior</td><td>----</td></tr>
<tr><td>Usability</td><td>Set A was superior</td><td>Set A was superior</td><td>Set A was superior</td><td>Set A was superior</td></tr>
</table>

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Introduction

Continued operations in desert areas, such as Iraq and Afghanistan, have identified the limitations of current cockpit cueing during flight in degraded visual environments (DVEs), such as brownout due to blowing sand and in fog. To increase survivability and mission effectiveness, aviators need technology that can assist during flight in DVEs.

In an effort to provide advanced technology to assist during flight in DVE, the Degraded Visual Environment Mitigation (DVE-M) program was established as an Army science and technology effort. The DVE-M program has focused on development of three technological components: advanced flight control laws, advanced pilot cueing, and an environmental sensor.

This study focused on evaluating flight control laws and advanced pilot cueing in a simulated DVE. Prior work in the DVE-M program resulted in advanced visual cueing symbology, tactile cueing, auditory cueing, and flight controls evaluated during simulation and flight. This study built upon previous work by assessing refinements to these advancements and comparing them to another symbology version. Additionally, all previous studies in the DVE-M program have utilized only experimental test pilots (XPs), who have typically had a high number of flight hours and prior experience with the technology under development in the DVE-M program. To gain a better understanding of the true functionality of these technologies in "regular" pilots, the present study used pilots who were not XPs and who had a diverse range of flight experience. This should help the program identify which aspects of the cueing system should be refined to assist pilots in the operational environment.

The primary objectives of the present study were the following: (1) compare a refined version of previous visual cueing symbology to an alternate version, (2) compare an advanced flight controls system to a current one, and (3) evaluate usability of the visual symbology as displayed on a helmet-mounted compared to a panel-mounted display. Secondary objectives of the study included assessing how these technologies affected workload and situational awareness, as well as garner feedback from the pilots on aspects of the technologies for future refinements.

Methods

Participants

Participants in the study included eight male UH-60 pilots (M_{age} = 37.75 years, SD_{age} = 6.20). The pilots consisted of Active Duty Army (n = 5), National Guard (n = 1), and Department of the Army Civilians (n = 2), with 7 to 27 years of military service (M = 15.63 years, SD = 7.09). The military ranks of the pilots included warrant officers from W-2 to W-4, and commissioned officers from O-2 to O-3. The pilots selected for inclusion in the study flew either the UH-60A/L or the UH-60M Black Hawk helicopter as their primary aircraft. UH-60 flight hours ranged from 450 to 4,100 hours (M = 2,118.75 hours, SD = 1,390.77), with total flight hours ranging from 520 to 4,200 hours (M = 2,260, SD = 1,389.87). Aviator's Night Vision Imaging System (ANVIS) experience ranged from 0 to 1,500 hours (M = 615, SD = 595.96).

Pilots were well rested prior to participating in the study, reporting 6 to 10 hours (M = 7.7) of sleep each night before participation. Additionally, pilots' consumption of caffeine and alcohol prior to study participation was minimal. These data were collected for the purposes of ensuring the accuracy of the biometric data, as sleep quantity and quality, and caffeine and alcohol intake can affect biometric data (e.g., Gilbert, Dibb, Plath, & Hiyane, 2000 [caffeine, nicotine]; Kähkönen, Wilenius, Nikulin, Ollikainen, & Ilmoniemi, 2003 [alcohol]).

Research Design

The study used a factorial repeated-measures design, with three-within subjects factors: symbology set (2 levels: A, B), display type (2 levels: Helmet Mounted Display [HMD], Panel Mounted Display [PMD]), and controls configuration (2 levels: Modernized Control Laws/Coupled Collective [MCLAWS/CCOL], Stability Augmentation System/Flight Path Stabilization [SAS/FPS]). All participants experienced each condition manipulation, resulting in eight flights under eight condition combinations completed (see Table 1 for conditions). Conditions were counterbalanced such that symbology set presentations were balanced across days, and display type and controls configurations were counterbalanced within each symbology set. Thus, participants completed either conditions one through four or five through eight on day one, with the order of those conditions counterbalanced. See Table 2 for condition orders.

Table 1. Study Conditions

Condition #	Symbology	Controls	Display
1	Set A	SAS/FPS	HMD
2	Set A	SAS/FPS	PMD
3	Set A	MCLAWS/CCOL	HMD
4	Set A	MCLAWS/CCOL	PMD
5	Set B	SAS/FPS	HMD
6	Set B	SAS/FPS	PMD
7	Set B	MCLAWS/CCOL	HMD
8	Set B	MCLAWS/CCOL	PMD

Table 2. Conditions Orders

Condition Order #	Day 1 Order of Conditions	Day 2 Order of Conditions
1	3, 1, 4, 2	6, 8, 5, 7
2	5, 7, 6, 8	2, 4, 1, 3
3	1, 3, 2, 4	7, 5, 8, 6
4	8, 6, 7, 5	4, 2, 3, 1

Materials

Mission Profile

The flight profile consisted of five maneuvers completed at four landing zone (LZ) segments: LZ Town, LZ Envoy, LZ Base, and LZ Ropes. All segments and maneuvers of the flight were performed with simulator conditions set to night, high dust, no starlight and low visibility. The flight took place during a simulated mission to drop off American troops at Osama Bin Laden's compound in Pakistan. Below are descriptions of each of the LZs or segments that were flown, and a depiction of the route (Figure 1). It should be noted, when analyzing data, LZs Town and Base were combined as these two included very similar maneuvers.

LZ Town.

This segment featured a takeoff maneuver in a brownout DVE. After reaching increased airspeed and altitude, the program transitioned to the en-route condition wherein participants experienced multiple types of terrain including both mountainous and desert. The pilot then completed an approach to landing and a landing in a brownout DVE.

LZ Envoy.

This segment featured a brownout degraded visual environment takeoff maneuver from LZ Town. After reaching increased airspeed and altitude, the pilot followed cues to navigate ascension of a mountainous terrain while maintaining appropriate airspeed. After passing through an approach gate, the pilot was instructed by the cueing system to decrease altitude and airspeed in an approach to hover. The pilot then hovered over LZ Envoy for 30 seconds in a brownout degraded visual environment over a pinnacle with an 8 degree landing slope and with a false horizon ahead of the aircraft. After completing the 30-second (s) hover, the pilot landed the helicopter on the 8-degree sloping pinnacle.

LZ Base.

During this segment, the pilot completed a takeoff from LZ Envoy from the 8-degree nose up sloping pinnacle. The pilot followed cues to increase altitude and airspeed. During the en-route phase of this segment, the pilot followed cues to navigate a highly mountainous terrain with a multitude of altitude manipulations. The pilot then landed the aircraft within a mountain basin in a desert, in a brownout DVE.

LZ Ropes.

Prior to this segment, the gross weight of the aircraft was set to 20,000 pounds to simulate troops had been picked up at LZ Base. During this segment, the pilot completed a takeoff in a brownout DVE within a mountain basin. The pilot then navigated a constantly changing terrain, flying over both mountains and desert, even flying low, parallel with a cliff-side. The pilot approached LZ ropes that was simulated to the precise dimensions of Osama Bin Laden's compound. The pilot then completed a 30 s hover at 30 feet (ft) above the ground within the walls of the compound. During this hover, the gross weight of the aircraft was decreased from 20,000 to 16,000 pounds by 1,000-pound increments to simulate the unloading of armed troops.

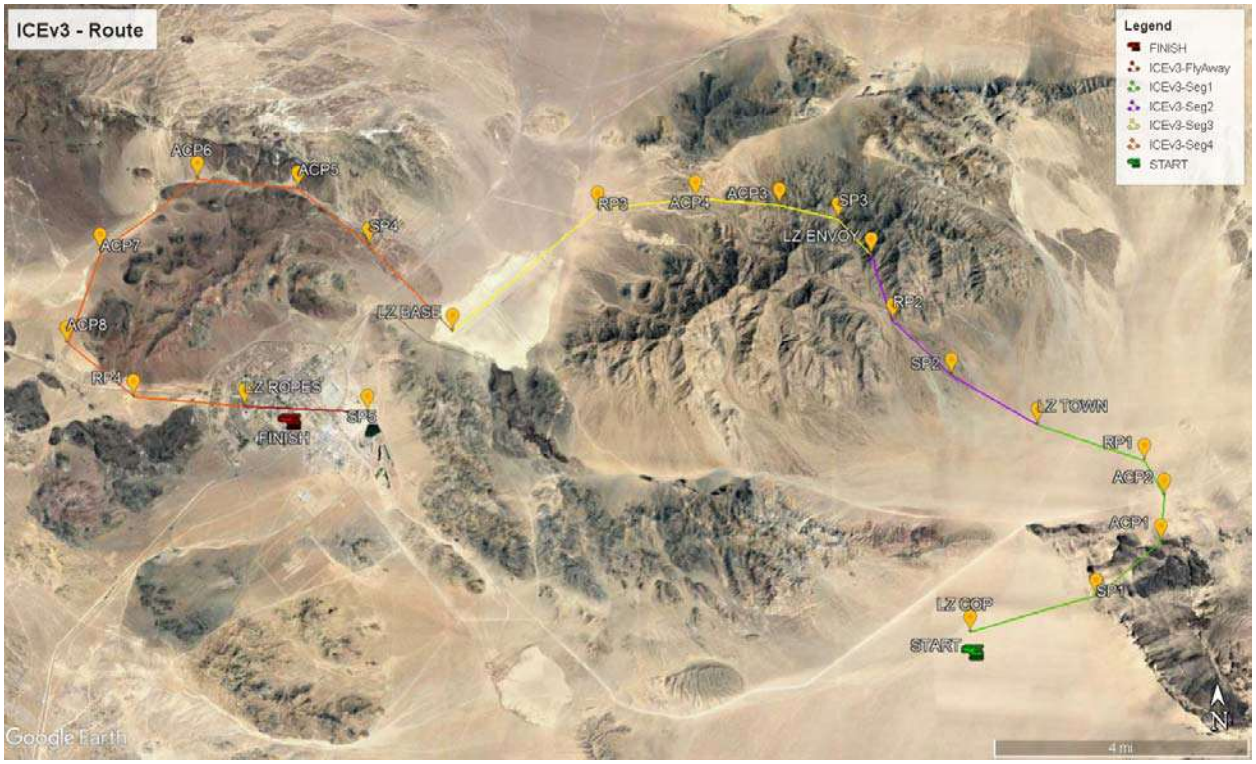


Figure 1. Flight route.

Maneuvers

The pilots completed standard maneuvers throughout each segment of the flight. The start and end points of each maneuver are listed in Table 3. The maneuvers included:

Takeoff.

This maneuver began with the helicopter on the ground with the parking brake enabled. The pilot completed an altitude over airspeed takeoff. The pilot was instructed to monitor the cueing system to take off from the ground and maintain a positive vertical speed and positive forward speed. The takeoff maneuver was completed at each of the four flight segments.

En-route.

This maneuver occurs after the pilot has reached an airspeed of 65 knots. During this maneuver, the pilot was instructed by the cueing symbology to follow the guided path and to maintain flight within the guided path parameters.

Approach.

This maneuver occurred after the pilot reached the approach gate. At this point, the pilot would decrease airspeed and altitude according to the cues provided by the system. This maneuver differs between the landing zone segments. During the LZ Town and LZ Base segments, the pilot approaches to a landing whereas during LZ Envoy and LZ Ropes, the pilot approaches a hover point. For MCCLAWS/CCOL conditions, coupled collective was engaged after passing the approach gate.

Hover.

This maneuver required the pilot to position the helicopter accurately above a guided hover point at 30 feet above the ground. The pilot was instructed to hold each hover for 30 seconds. For MCCLAWS/CCOL conditions, position hold was engaged at the start of the hover.

Landing.

This maneuver required the pilot to land the aircraft at the specified landing zones by decreasing speed and altitude appropriately.

Flight Simulator

All flights were conducted in the NUH-60FS Black Hawk helicopter simulator. The simulator is fully accredited by the Directorate of Simulations (DoS) and by the Program Executive Office Simulations, Training, and Instrumentation (PEO STRI) as a 6-degree of freedom, full-motion, and full visual (Level D equivalent) NUH-60FS Black Hawk helicopter flight simulator. The NUH-60FS possesses an enhanced brownout dust model capable of accurately simulating blowing and billowing dust. The simulator also features Dell XIG visual image generators that can simulate numerous natural helicopter environment surroundings including day, dusk, night, dust, snow, rain, clouds, Night Vision Goggle (NVG), and infrared characteristics.

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 compute absolute deviations and root-mean-square deviations (RMSD) from the target symbology parameters for each maneuver within a flight segment. RMSD values were computed by summing the squared error from the actual flight parameter and the target symbology parameter, dividing this squared deviation by the number of data points, and taking the square root of this quotient. For landing and approach, radial error was computed by summing the squared lateral and longitudinal deviations from the set touchdown/hover point together and taking the square root of this result. Metrics were derived for each phase of flight (en-route, approach, hover, and landing) for each LZ (Base, Town, Envoy, and Ropes), when appropriate. Takeoff performance was not analyzed. Table 4 summarizes the metrics available for each phase of flight.

Table 3. Maneuver Definitions within Data

Maneuver	Start	End
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
Hover	1) When aircraft lateral distance from landing point is < 250ft 2) Waypoint type is a hover point 3) Commanded horizontal speed guidance is < 2.0 knots	Research pilot advances waypoint index to command pilot to hover down to landing point
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

Table 4. Flight Performance Metrics

Metric	En-route	Approach	Hover	Landing
RMSD Lateral Deviation (ft)	X	X		
RMSD Speed Deviation (kts)	X	X		
RMSD Vertical Deviation (ft)	X			
RMSD Heading Deviation (deg)		X	X	
RMSD Longitudinal Deviation (ft)				
RMSD Altitude Deviation from 30 (ft)			X	
Touchdown Lateral Speed (kts)				X
Touchdown Heading Deviation (deg)				X
Radial Error (ft)			X	X

Note. Radial error for hover was an RMSD distance and for landing was an absolute distance.

Symbology Sets and Cueing

Both symbology sets utilized visual cues displayed on a PMD or through an HMD, auditory cues utilizing a monaural voice synthesizer and monaural sounds, and tactile cues through belts worn by the pilots that produced vibrations as well as tactors installed within the aircraft seats.

Symbology Set A.

Full descriptions and figures of the symbology set features can be found in Appendix A. Generally, Symbology Set A utilized visual cues displayed on a PMD and HMD, auditory cues utilizing a monaural voice synthesizer and monaural sounds, and tactile cues in the aircraft seat, shoulder harness and belts worn by the pilots. One differentiating feature of note is the use of the "highway in the sky." Symbology Set A required the pilots to maintain altitude and lateral positioning by maintaining their position within a magenta box that served as the flight path. The use of this symbology set ensured that the pilots remained at the appropriate altitude and lateral position because if they veered outside of the flight path, a tactile cue alerted them to return to the correct position. Further, the highway in the sky provides directional information.

Symbology Set B.

Full descriptions and figures of the symbology set features can be found in Appendix B. Generally, Symbology Set B also utilized visual cues displayed on a PMD and HMD, auditory cues utilizing a monaural voice synthesizer and monaural sounds, and tactile cues in the aircraft seat, shoulder harness and belts worn by the pilots. One differentiating feature of Symbology Set B is the use of an earth-referenced magenta chevron ground course track. Similar to the flight path described in Symbology Set A, the chevron ground track serves as a directional course pointer and points directly to the next turn point. The chevron ground track does not provide lateral drift information, nor does it provide altitude information, although, if the pilot deviated from the flight path, a tactile cue alerted them to return to the correct position.

Tactile Cues.

The study used belt, shoulder harness, and seat cushion tactors operated under the Tactile Situation Awareness System (TSAS) algorithms for speed, drift, and altitude control. Tactile cues provided feedback based on the maneuver being flown. Using positioning data from existing aircraft sensory studies, TSAS provided haptic cues via an array of tactors on the body.

Aural Cues.

Aural alerts for altitude, heading, and speed/drift were provided via HGU-56/P rotary-wing aircrew helmets. Aural cues provided different feedback based on the phase of flight. A breakdown of aural cues for each phase of flight is provided in Appendix C.

Flight Controls

Stability Augmentation System/Flight Path Stabilization.

The Automatic Flight Control System (AFCS) enhances the stability and handling qualities of the helicopter and provides autopilot functions. It is comprised of five basic subsystems: Stabilator, SAS, Trim Systems, FPS and Coupled Flight Director (FD). The AFCS functions include pitch and roll attitude hold, FD mode, heading hold, and turn coordination. The SAS enhances dynamic stability and provides short term rate damping in the pitch, roll, and yaw axes. The trim system provides control positioning and force gradient functions as well as basic autopilot functions with FPS engaged. The FPS maintains helicopter pitch and roll attitude as well as airspeed and heading during cruise flight and provides a coordinated turn feature at airspeeds above 50 knots.

MCLAWS/CCOL.

The MCLAWS software enhanced the simulator's response type from the baseline rate damping response type to an attitude-command/attitude hold (ACAH) response type in pitch and roll up to 60 knots when the MCLAWS control system was engaged. Above 60 knots, the MCLAWS switched to a SAS-like rate response type. The MCLAWS directional axis provides a rate-command/direction hold (RCDH) response type at all airspeeds.

The CCOL mode integrated the vertical axis augmentation with the ICE guidance, allowing the altitude hold mode to follow the ICE altitude and vertical velocity commands. For approaches to landing, the CCOL maintains the commanded rate of descent until the first main landing gear weight-on-wheel switch is activated; it then continues to command the collective full down to complete the landing. For approaches to hover, the CCOL automatically transitions to a radar altitude hold mode until de-selected by the pilot.

Subjective Measures

Demographic Questionnaire.

Basic demographic information was collected at the beginning of participation from each pilot including age, gender, rank, and military service duration, etc. (see Appendix D). Flight experience data including primary aircraft type, total flight hours, UH-60 Black Hawk flight hours, Aviator's Night Vision Imaging System (ANVIS) hours, and heads up display (HUD) hours for both night and day systems were also collected.

Sleep Questionnaire.

The Sleep Questionnaire was administered to each pilot on each morning of their participation (see Appendix D). Pilots were asked how many hours they slept the previous night, to rate the quality of their sleep from 1 ("best sleep ever") to 9 ("worst sleep ever"), and to rate their degree of current sleepiness using the Stanford Sleepiness Scale (Hoddes, Dement, & Zarcone, 1972). Pilots were also asked to indicate if caffeine or alcohol were consumed in the past 24 hours, and if so, when and how much.

Training Questionnaire.

The Training Questionnaire (see Appendix D) was administered to each participant upon completing each block of missions by symbology type. Pilots rated their level of training satisfaction on a 5-point Likert scale, with anchors of "strongly disagree," "disagree," "neither agree nor disagree," "agree," and "strongly agree" for 7 question items.

Motion Sickness Assessment Questionnaire.

The Motion Sickness Assessment Questionnaire (MSAQ) (see Appendix D); was developed and validated to assess motion sickness as a multidimensional construct (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001). The MSAQ is comprised of 16 questions covering four clusters of symptoms: gastrointestinal (G), central nervous system (C), peripheral nervous system (P), and sopite-related (S) symptoms with responses ranging from 1 ("not at all") to 9 ("severe"). The MSAQ was administered after the completion of each mission.

Bedford Workload Rating Scale.

To estimate the level of workload during each phase of flight (takeoff, en-route, approach, and hover), pilots provided workload ratings using the Bedford Workload Rating Scale (see Appendix D). The Bedford Workload Rating Scale is a uni-dimensional scale and has been used extensively by the military, civil, and commercial aviation communities for pilot workload estimation (Roscoe & Ellis, 1990). It requires pilots to rate the level of workload associated with a task based on the amount of spare workload capacity they estimate they have to perform additional tasks. The response scale ranges from 1 ("insignificant workload") to 10 ("task abandonment due to high workload"). Spare workload capacity is an important commodity for pilots because they are often required to perform several tasks concurrently. Workload ratings were collected after the completion of each mission.

Situation Awareness Rating.

To estimate the level of internal and external situation awareness (SA) they had when performing flight tasks, pilots provided ratings on a custom rating scale from 1 ("very high level of SA") to 10 ("very low level of SA") (see Appendix D). Internal SA refers to awareness of the aircraft state and external SA refers to awareness of the external environment around the aircraft. Internal and external SA ratings were collected after the completion of each mission. This rating was developed by U.S. Army Research Laboratory's (ARL's) research team members. Examples of internal and external SA include:

Internal SA Examples: Altitude / Vertical Speed, Air Speed / Ground Speed, LZ / Hover Position, Drift, Power Margin, Attitude, Heading

External SA Examples: Terrain Slope, Terrain Roughness, Features in the Landing Zone, Obstacles, Vehicles, Personnel, Threats

Cueing Usability Questionnaire.

The Cueing Usability Questionnaire, developed by ARL research team members, asked the pilot to rate the usability of various aspects of the configuration (e.g., 2D symbology, guidance symbology, 3D conformal symbology, sensor visualization, aural cueing, tactile cueing, and controllability of the aircraft) for each phase of flight (i.e., takeoff, en-route, approach, and hover). The questionnaire used a 6-point Likert scale with anchors of "Excellent," "Very Good," "Good," "Poor," "Very Poor," and "Unsatisfactory." Additionally, open-ended questions were asked and responses were collected. Cueing usability ratings were collected after the completion of each mission.

Additional open-ended responses were collected upon completion of all missions in each symbology type (Set A and Set B). At the same time, a slightly modified System Usability Scale (SUS) (Brooke, 1996) (see Appendix D) was administered.

The Cueing Usability Questionnaire (see Appendix D) was administered when the evaluation pilot completed all of their test points. This questionnaire allowed the pilot to rate the overall usability of each ICE component, and provide additional comments. A 6-point scale was used, ranging from “unsatisfactory” to “excellent.”

Trust in Automation Questionnaire.

Pilots rated their level of trust for two aspects of the system: the cueing and the flight control & guidance algorithms. The Trust in Automation Questionnaire (see Appendix D), developed by the ARL research team, included four question items with responses rated on a 5-point scale, with anchors of “strongly disagree,” “disagree,” “neither agree nor disagree,” “agree,” and “strongly agree.” Trust in automation ratings were collected after the completion of each mission.

Overall Preference Questionnaire.

The overall preference questionnaire (see Appendix D) asked the pilot to choose their preference of features for symbology type (Set A or Set B), flight control mode (SAS/FPS or MCLAWS/CCOL), and display type (HMD or PMD) for each phase of flight (takeoff, en-route, approach, and hover). Additionally, pilots were asked to choose what they prioritized during each phase of flight: task performance, workload, or situation awareness. Overall preferences were collected on the last day of participation after the completion of all missions.

Biometric Collection Devices

Electroencephalogram.

Electroencephalogram (EEG) data were collected using Advanced Brain Monitoring’s B-Alert X24 wireless wet electrode system. This system collects EEG data at a sampling rate of 256 Hz from 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, P4, T5, T6, O1, O2). Reference electrodes were placed at the left and right mastoid bones. The acquisition software used Advanced Brain Monitoring signal processing algorithms to detect and remove artifacts (spikes, excursions, amplifier saturations, electromyography, and eye blinks) from the EEG signal. Additionally, 50, 60, 100, and 120 Hz notch filters and a low pass finite impulse response filter were applied to the EEG signal online during data acquisition. Power spectral density (PSD) was then computed automatically by applying the Fast Fourier Transformation to the decontaminated EEG signal, resulting in PSD values (absolute and relative) being computed on a second-by-second epoch basis in 1 Hz frequency bins (1-40 Hz). Additionally, this EEG system provides cognitive state classification algorithms (engagement, distraction, and workload) derived from absolute and relative PSD values of candidate EEG channels. These algorithms have been previously validated (Berka et al., 2007; Johnson et al., 2011) and allow for individualization and generalization of the classification data; the engagement and workload classifications were used as outcome measures in this study. While two workload classifications are provided by the system, only the data from the classification based on the forward digit span task was used in analyses, as this model has been found to fit approximately 85% of the population.

The workload classifications are derived using a linear discriminant function analyses (DFA) with two classes, high and low workload, while the engagement classification is derived from a four-class linear discriminant function analysis. EEG data from differential channels C3C4, CzPOz, F3Cz, F3C4, FzC3, and FzPOz for the workload model, and FzPOz, CzPOz for the engagement classification model (Berka et al., 2007) are used to derive cognitive state classification probabilities. The workload classification provides an indication of working memory load and processing, and provides a value ranging from zero to one, with values closer to one indicative of a higher probability of the participant experiencing a greater workload. The engagement and distraction classifications also provide a numeric value ranging from zero to one, with values closer to one indicating a higher probability the participant is experiencing the given cognitive state. The engagement classification is associated with active attention and vigilance constructs. To simplify, these values can be thought of as percentages ranging from 0 to 100%. Participants completed three neurocognitive tasks (i.e., three choice vigilance task, eyes open vigilance task, and eyes closed vigilance task) that were used to create a normalized engagement metric.

Electrocardiogram.

Electrocardiogram (ECG) data for heart rate variability (HRV) and heart rate were collected using the Biopac MP150 ECG100C system. This system samples at 1000 Hz, with an online filter of LPN 35 Hz and HP 0.5 Hz. Three ECG electrodes were placed on each pilot in a Lead II configuration (one on each collarbone, one on the lower left ribcage). Prior to data collection each day, a 5-minute resting baseline was collected to use in subsequent analyses.

Data collected from the ECG were reduced using AcqKnowledge version 4.2. The data were first filtered with an offline high pass filter at 1 Hz and a band stop filter at 60 Hz. Artifacts were identified through visual inspection and corrected for using linear interpolation. AcqKnowledge's automated HRV analyses tool was used to extract low- and high-frequency values. The tool first extracts RR intervals using a modified Pan-Tompkins QRS detector. The RR intervals were then re-sampled to a continuous sampling rate using cubic-spline interpolation to generate the continuous time-domain representation of RR intervals. A Welch periodogram was then used to generate the Power Spectral Density values. Data extracted for analyses include the normalized units of high frequency (HFnu) and low frequency (LFnu), which were normalized using the following: HFnu = HF/(LF + HF) and LFnu = LF/(LF + HF). The present study used the HFnu/LFnu ratio as a measure of HRV. Beats per minute were also extracted for each segment to provide heart rate values. All ECG data were baseline-corrected for analyses in order to account for individual day-to-day variability.

Respiration.

Respiration data were collected using the Biopac Bionomadix® respiration transducer belt with the MP150 RSP100C amplifier module. Respiration were sampled at 50 Hz with a low pass online filter set at 10 Hz. Respiration rate was collected through a respiration belt and transducer that were placed around the pilot's abdomen or chest. Prior to data collection each day, a 5-minute resting baseline as collected to use in subsequent analyses. Data extracted for analyses were respiration rate in breaths per minute. Following data collection, data were filtered using a bandpass FIR filter between 0.05 Hz and 1 Hz. Data were then visually inspected for any artifacts, which were corrected using linear interpolation. Respiration rate was then extracted in breaths per minute and was baseline corrected for data analyses.

Visual Gaze.

Pilots' visual gaze and dwell times were collected with a Tobii® Pro Glasses 2 eye tracking system (see Appendix E, Figure E1). This system was selected because of the form factor allowed for integration with the bi-ocular HMD. The Application Programming Interface (API) for the Tobii® system was used to integrate the eye tracking system with the USAARL data collection system. This allowed continuous data collection of pilot eye positions during all conditions and live monitoring of gaze position during HMD conditions. Eye gaze positions were mapped onto static representations of the symbology sets used during the experiment to determine the proportion of time that the pilot had visual fixations in defined areas of interest. Pictorial representations of the defined areas of interest (AOI) for each symbology set are in Appendix E, Figures 2 and 3. Three phases of flight (takeoff, en-route, and approach) were analyzed for each flight segment. The phases of flight were automatically defined by the simulator flight events and all of these times were marked automatically by the simulator through the Tobii® API. Statistical analyses were conducted for the following AOIs on the PMD: center of PMD, radar altitude, and speed.

Procedure

Pilots participated in the study over a period of two to three consecutive days. On days one and two, pilots reported to the laboratory at 0800 hours for a study overview briefing, safety information, and scheduling explanation. Following the initial briefings, they completed a questionnaire to assess the previous night's sleep, current level of sleepiness, and caffeine/alcohol/nicotine intake during the previous 24 hours. Next, pilots were familiarized with the symbology set that they would be flying that day (A or B) through a PowerPoint training provided by the study's research pilot lasting approximately 1 hour. During this initial training session, the research pilot provided an overview of the types of cueing to be used in the study (i.e., visual cueing, auditory cueing, tactile cueing), the functionality of the MCLAWS/CCOL controls configuration, and symbol descriptions for each phase of flight.

After pilots received initial PowerPoint training on the symbology set and cueing, they completed approximately 3 hours of simulator training where they flew a training route and completed each flight maneuver to demonstrate functionality of the cueing. The research pilot determined when the participant pilot was proficient on the cueing sets. Once proficiency was established, pilots took a break for lunch where they completed the demographic questionnaire (day one only), and reviewed the questionnaires to be completed between flights. Next, pilots were fitted with the biometric data collection devices (EEG, ECG, respiration belt, and eye tracking glasses). Pilots then completed baseline recordings for EEG, ECG, and respiration.

Following baseline procedures, the pilots entered the simulator. The eye tracking glasses were first calibrated, after which bore sighting was done for the HMD conditions. Pilots then flew through their first four conditions with questionnaires completed between flights. The second day followed the same procedures with the second symbology set, and any flights unable to be finished during the first two days of testing were completed on a third day. After completing test flights, pilots exited the simulator, biometric devices were removed, and the pilots completed a series of usability questionnaires and participated in an after action review (AAR).

Statistical Approach and Quality Control

Series of repeated measures analysis of variance (ANOVAs) were conducted to test the effects of symbology set (A versus B), controls (SAS/FPS versus MCLAWS/CCOL), and display type (HMD versus PMD) on flight performance metrics, biometric measures, and eye gaze measures for phase of flight and LZ. Analyses were conducted using International Business Machines Statistical Package for the Social Sciences (IBM SPSS) Version 21. Both flight performance and biometric data were first examined for outliers. Outliers were identified as greater than 2 standard deviations (SDs) away from the mean. Data were also inspected for missing data. The EEG data had the greatest amount of missing values (~20%) whereas the remainder variables, including flight performance, contained fewer than 10%. As such, multiple imputation using the Markov Chain Monte Carlo (MCMC) was completed to replace missing EEG values prior to analyzing. For the remaining metrics, participants with missing data (e.g., flight performance, etc.) were excluded list-wise on an analysis-by analysis basis. A 2 (Symbology Set) x 2 (Controls) x 2 (Display) repeated measures design used to analyze performance data for approach, hover, and landing, and biometric data for en-route, approach, and hover. A 2 (Symbology Set) x 2 (Controls) was used to examine eye gaze data for takeoff, en-route, approach and hover. For en-route performance, a 2 (Symbology Set) x 2 (Display) design was used to analyze data because MCLAWS/CCOL was disabled during en-route flight. Results are presented below by maneuver type.

For subjective measures, MSAQ subscale scores and total score were computed and a Wilcoxon signed rank test was used to explore differences in MSAQ total score between the HMD and PMD conditions. For the Bedford Workload Rating and Situation Awareness Rating, descriptive statistics were computed and Wilcoxon signed rank tests were used to explore differences in workload ratings for symbology set (A versus B), display type (HMD versus PMD), and controls (SAS/FPS versus MCLAWS/CCOL). Subjective analyses examined overall responses to maneuvers aggregated across LZs.

It should also be noted that 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. Parametric methods were used to analyze the data as there is not currently a comparable non-parametric method available to analyze factorial repeated-measures data.

Results

Initial Analysis of Order Effects

Potential order effects for performance and biometric measures were examined by using condition order as a between subjects factor. Only one significant order effects was found for flight performance. Order significantly affected LZ Base/Town en-route vertical deviations such that those who completed the flights in condition order 1 (see Table 3 for condition orders; M = 55.27, SE = 2.17) had significantly less vertical deviation than those that completed the flight in condition orders 2 (M = 72.58, SE = 2.17) or 3 (M = 78.14, SE = 2.17).

Crashes

A total of 11 crashes occurred throughout the study. Crashes were qualitatively examined to identify any patterns. Of the 11 crashes, 5 were with the same participant, while the remaining 6 crashes occurred amongst 3 other pilots. Seven of the crashes occurred during takeoff, one during landing, one during approach, and two during hover. The crashes occurred at each of the LZs. Notably, 8 of the 11 crashes occurred using Symbology Set B and 7 of the 11 crashes occurred while MCLAWS/CCOL were used.

Eye Gaze Takeoff

The mean proportions of fixations in each area of interest during the takeoff segment across all pilots, landing zones, and control types is shown in Figures 2 and 3. Eye gaze heat maps for Symbology Sets A and B during takeoff are displayed in Figures E4 and E5, respectively, in Appendix E.

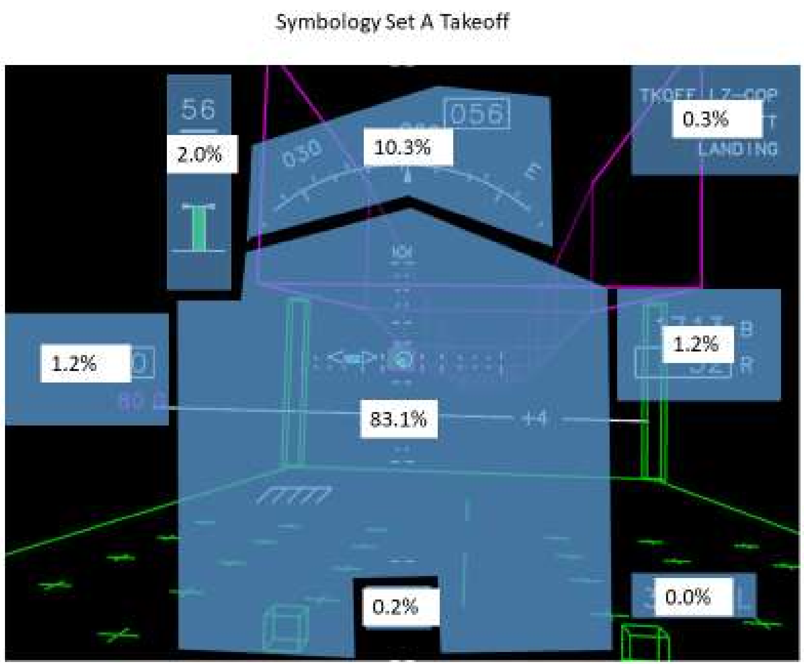


Figure 2. Symbology Set A takeoff.

Symbology Set B Takeoff

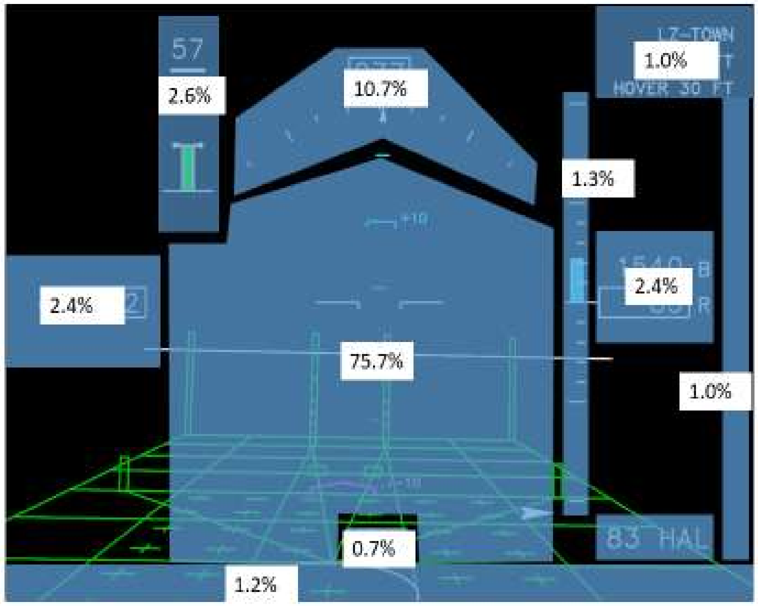


Figure 3. Symbology Set B takeoff.

Statistical tests were performed for 4 areas of interest of concern for system designers: altitude, center of PMD, heading, and speed. No significant main effects were found for takeoff eye gaze metrics.

En-route Performance

Means, standard errors, and *F* statistics for the en-route performance metrics (lateral deviation, vertical deviation, speed deviation) are displayed in Table 5. Symbology set had a significant effect on en-route lateral and vertical deviations for all LZs. Additionally, symbology set had a significant effect on speed deviation for LZs Base/Town and Envoy. Across the significant main effects of symbol set, Symbology Set A had superior performance when compared to Symbology Set B. Moreover, effect sizes were large. No other significant effects were found for en-route performance.

Table 5. En-route Performance for the Main Effect of Symbology Set

	Symbology Set A		Symbology Set B				
	M	*SE*	*M*	*SE*	*F*	*p*	η_p^2
Base/Town							
Lateral Deviation (RMSD ft)	34.90	3.00	91.67	5.03	248.40	< .001	.97
Vertical Deviation (RMSD ft)	37.69	1.67	98.33	6.13	100.20	< .001	.94
Speed Deviation (RMSD kts)	11.99	0.81	15.12	1.03	27.34	< .001	.80
Envoy							
Lateral Deviation (RMSD ft)	38.08	1.41	120.65	12.71	46.81	< .001	.87
Vertical Deviation (RMSD ft)	46.27	4.07	212.78	28.21	34.52	< .001	.83
Speed Deviation (RMSD kts)	19.12	1.31	23.46	1.47	5.80	.047	.45
Ropes							
Lateral Deviation (RMSD ft)	36.43	2.79	86.87	8.72	53.98	< .001	.89
Vertical Deviation (RMSD ft)	28.69	0.96	58.34	3.90	49.56	< .001	.88
Speed Deviation (RMSD kts)	12.19	0.79	12.41	0.72	0.62	.457	.08

En-route Biometrics

The en-route biometric data only found significance for metrics during the LZ Base/Town leg of the flight. The main effect of display type was significant for the EEG workload index at LZ Base/Town, $F\,(1, 7) = 8.66$, $p = 0.02$, $\eta_p^2 = 0.55$. Workload index values were higher for PMD ($M = 0.80$, $SE = 0.02$) compared to HMD ($M = 0.77$, $SE = 0.02$). There was a significant interaction between symbology set and display type for respiration, $F\,(1, 5) = 17.44$, $p = 0.009$, $\eta_p^2 = 0.77$. Follow up tests found no significant differences, however, when looking at symbol sets at each level of display, respiration rates appeared marginally lower with symbol set B displayed on HMD compared to PMD. (See Figure 4). Additionally, a significant symbology set by display interaction was found for the EEG workload index, $F\,(1, 7) = 10.59$, $p = 0.01$, $\eta_p^2 = 0.60$. Follow up tests found when Symbology Set B was displayed on PMD subjects' workload values were greater ($M = 0.817$, $SE = 0.021$) than when Set B was displayed on HMD ($M = 0.747$, $SE = 0.029$). No significant differences were found with Symbology Set A. Full results tables are located in Appendix G.

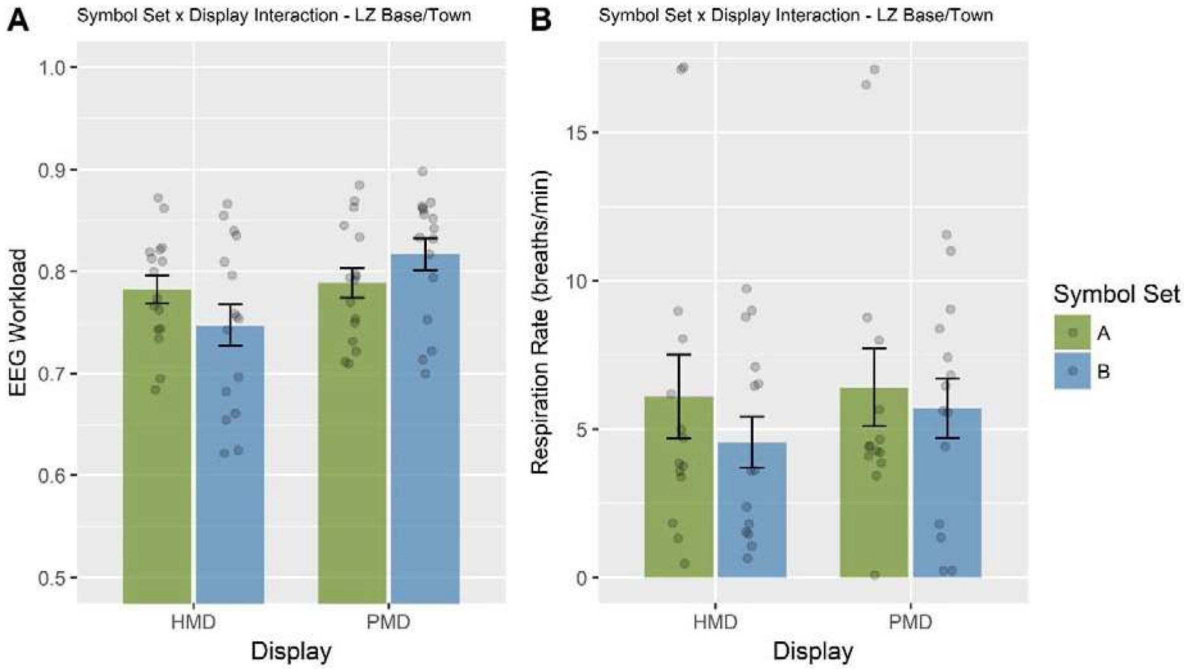


Figure 4. Symbology Set x Controls interaction for en-route LZ Base/Town EEG workload (A) and respiration rate (B). Bars represent means, dots represent individual observations, and error bars represent ± 1 standard error of the mean.

Eye Gaze En-route

The mean proportions of fixations in each area of interest during the en-route segment across all pilots, landing zones, and control types is shown in Figures 5 and 6. Eye gaze heat maps for Symbology Sets A and B during the en-route phase are displayed in Figures E6 and E7, respectively, in Appendix E.

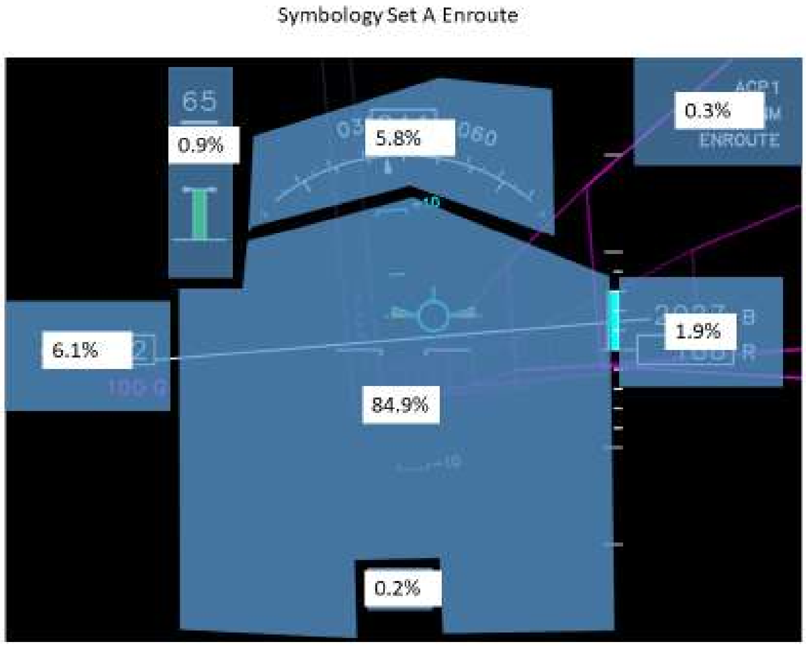


Figure 5. Symbology Set A en-route.

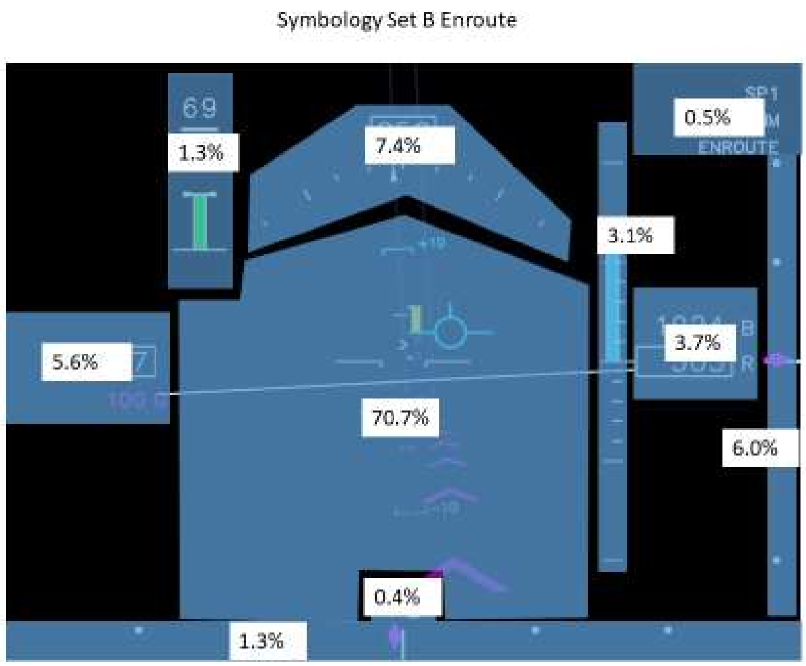


Figure 6. Symbology Set B en-route.

Statistical tests were performed for 4 areas of interest of concern for system designers: altitude, center of PMD, heading, and speed.

Symbology set had a significant effect on en-route altitude AOI fixations for LZ Town, $F(1, 7) = 5.761$, $p = 0.047$, $\eta_p^2 = 0.451$. No other significant main effects were found for en-route eye gaze metrics. Figure 7 depicts the differences between symbol sets on altitude means for AOIs of en-route at LZ Town.

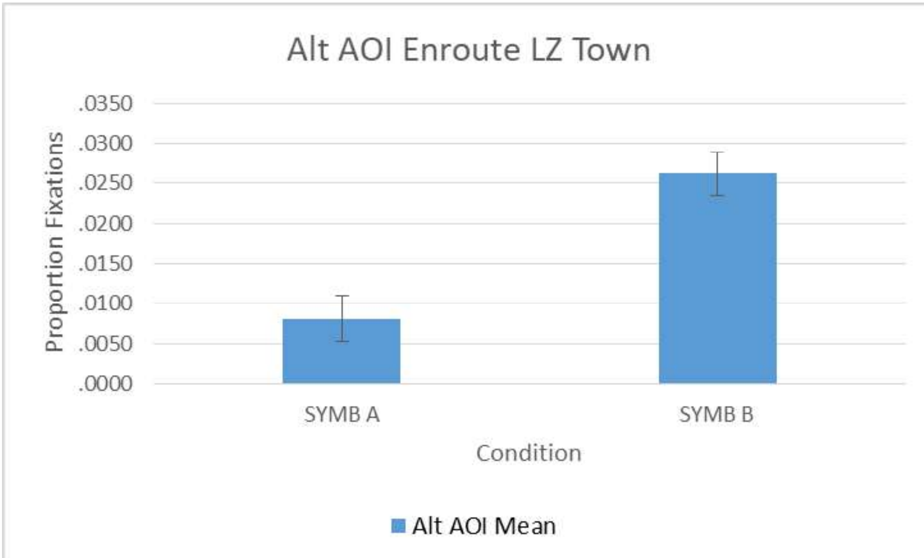


Figure 7. Altitude means for AOIs of en-route at LZ Town.

Approach Performance

Symbology set had a significant effect on LZ Envoy and Ropes approach speed deviations. Symbology set also had a significant effect on LZ Envoy approach lateral deviations. In each case, participants performed better with Symbology Set A compared to Symbology Set B (see Table F1, Appendix F). Additionally, the main effect of controls was significant for speed deviations only during LZ Ropes, $F(1, 6) = 75.14$, $p < .001$, $\eta_p^2 = .63$. Speed deviations were less for this approach when participants used MCLAWS/CCOL ($M = 4.22$, $SE = 0.48$) compared to SAS/FPS ($M = 5.64$, $SE = 0.58$) controls.

A significant symbol set by controls interaction was also found for LZ Base and Town approach lateral deviations, $F(1, 7) = 22.34$, $p = .002$, $\eta_p^2 = .76$. This two-way interaction was qualified by a significant three-way interaction, $F(1,7) = 7.12$, $p = .032$, $\eta_p^2 = .50$. Follow up analyses revealed no significant differences between control types when either display was used in conjunction with Symbology Set A. However, when participants flew with Symbology Set B in the PMD configuration, lateral deviation deviations were significantly less with SAS/FPS controls ($M = 20.62$, $SE = 4.60$) than MCLAWS/CCOL ($M = 31.11$, $SE = 4.38$) for this approach. Figure 8 displays this interaction.

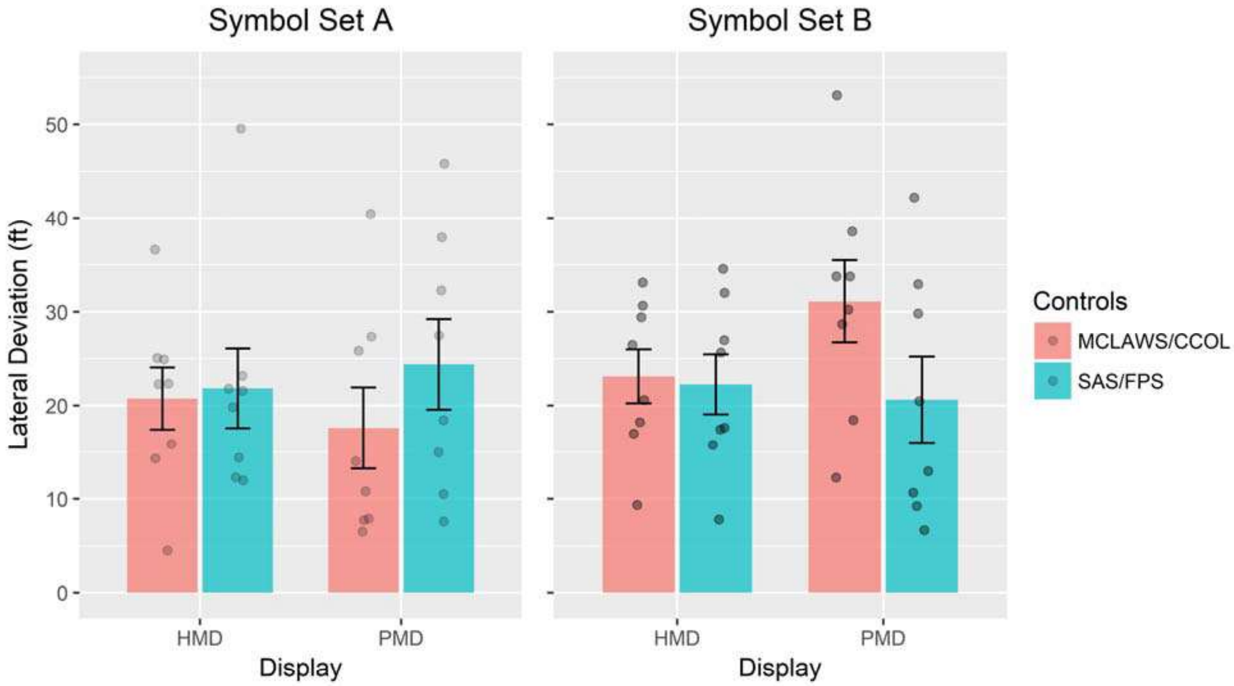


Figure 8. Symbology Set x Display x Controls interaction for LZ Base/Town approach lateral deviation. Bars represent means, dots represent individual observations, and error bars represent ± 1 standard error of the mean.

Approach Biometrics

Controls had a significant effect on the EEG workload index at LZ Base/Town, $F(1, 7) = 6.51$, $p = 0.04$, $\eta_p^2 = 0.48$, with higher workload values for MCLAWS/CCOL conditions ($M = 0.823$, $SE = 0.02$) compared to SAS/FPS conditions ($M = 0.805$, $SE = 0.02$). Additionally, the main effect for controls was significant for both the EEG workload, $F(1, 7) = 12.32$, $p = 0.01$, $\eta_p^2 = 0.64$, and engagement, $F(1, 7) = 21.65$, $p = 0.002$, $\eta_p^2 = 0.76$, indices at LZ Envoy. For both indices MCLAWS/CCOL (workload, $M = 0.83$, $SE = 0.02$; engagement, $M = 0.72$, $SE = 0.04$) conditions produced higher values compared to SAS/FPS (workload, $M = 0.81$, $SE = 0.02$; engagement, $M = 0.63$, $SE = 0.04$) conditions.

There was also a significant main effect of display on the EEG workload index at LZ Base/Town, $F(1, 7) = 18.27$, $p = 0.004$, $\eta_p^2 = 0.72$. Workload values were higher for the PMD display conditions ($M = 0.827$, $SE = 0.02$) compared to the HMD display conditions ($M = 0.801$, $SE = 0.02$). Further, three significant symbol set by display interactions were found for the EEG workload index at LZ Base and Town ($F[1, 7] = 33.81$, $p = 0.001$, $\eta_p^2 = 0.83$), Envoy ($F[1, 7] = 24.66$, $p = 0.002$, $\eta_p^2 = 0.78$), and Ropes ($F[1, 7] = 5.70$, $p = 0.050$, $\eta_p^2 = 0.45$).

Follow up tests for the interactions found that during LZ Base and Town approaches, Symbology Set A displayed on HMD resulted in higher workload values ($M = 0.824$, $SE = 0.02$) compared to Symbology Set B ($M = 0.78$, $SE = 0.03$) displayed on HMD, but no significant differences when both were displayed on PMD. Additionally, when Symbology Set B was displayed on PMD it resulted in significantly higher workload values ($M = 0.84$, $SE = 0.02$) than when displayed on HMD ($M = 0.78$, $SE = 0.03$). Similar results were found for LZ Envoy, where significantly higher workload values resulted from Symbology Set B displayed on PMD (*M* = 0.84, *SE* = 0.02) compared to HMD (*M* = 0.80, *SE* = 0.02); no significant differences were found with Set A. This was found again for LZ Ropes, Symbology Set B displayed on PMD (*M* = 0.83, *SE* = 0.02) produced greater workload values than displayed on HMD (*M* = 0.80, *SE* = 0.02). See Figure 9 below.

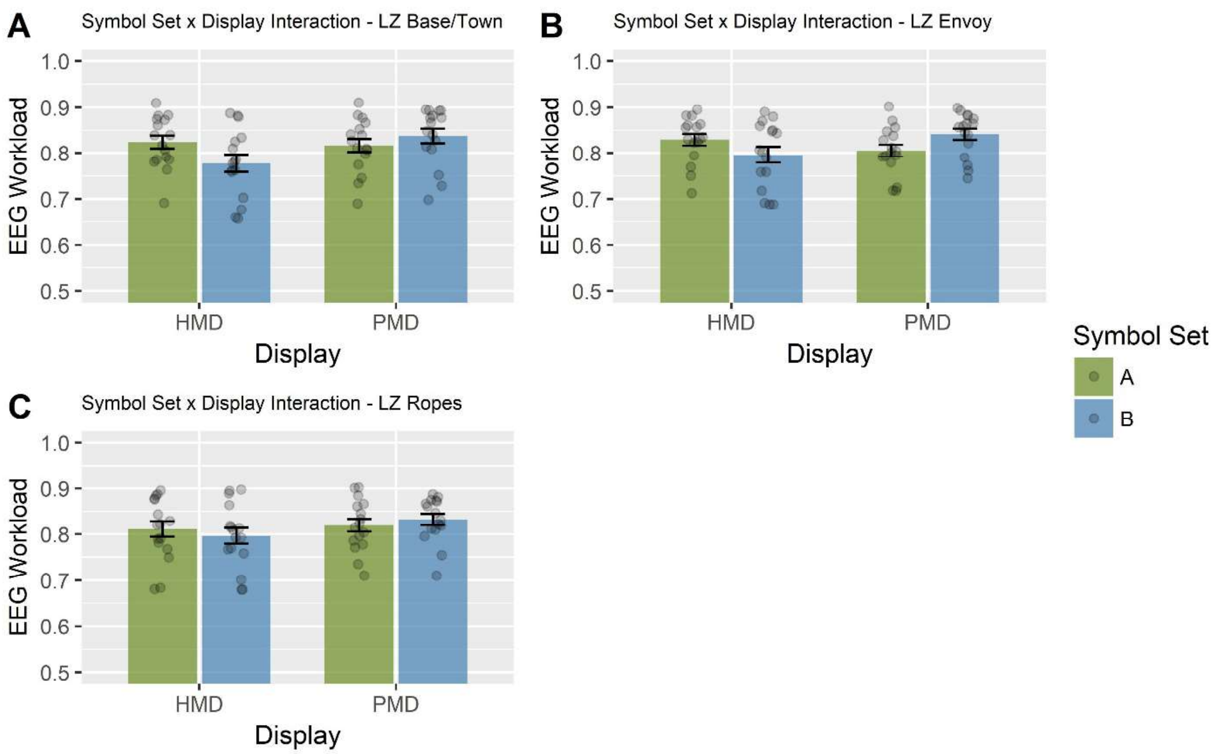


Figure 9. Symbology Set x Display interactions for en-route LZ Base/Town (A), Envoy (B), and Ropes (C) approach EEG workload. Bars represent means, dots represent individual observations, and error bars represent ± 1 standard error of the mean.

Further, there were significant controls by display interactions found for the HRV values at LZ Ropes, $F(1, 5) = 11.98$, $p = 0.018$, $\eta_p^2 = 0.71$, and the respiration rates at LZ Base and Town, $F(1, 5) = 8.91$, $p = 0.031$, $\eta_p^2 = 0.64$. Follow up tests for HRV found a lower value when using PMD (*M* = 2.17, *SE* = 1.07) compared to HMD (*M* = 3.58, *SE* = 1.69) while using FPS/SAS controls, but no significant differences when using MCLAWS/CCOL (see Figure 10). Follow up tests for respiration rate found no significant differences, however, respiration rates were marginally higher for PMD compared to HMD when using the MCLAWS/CCOL configuration, with no marginal differences for display type while using SAS/FPS (see Figure 9 above). See Table G2 in Appendix G for main effects results.

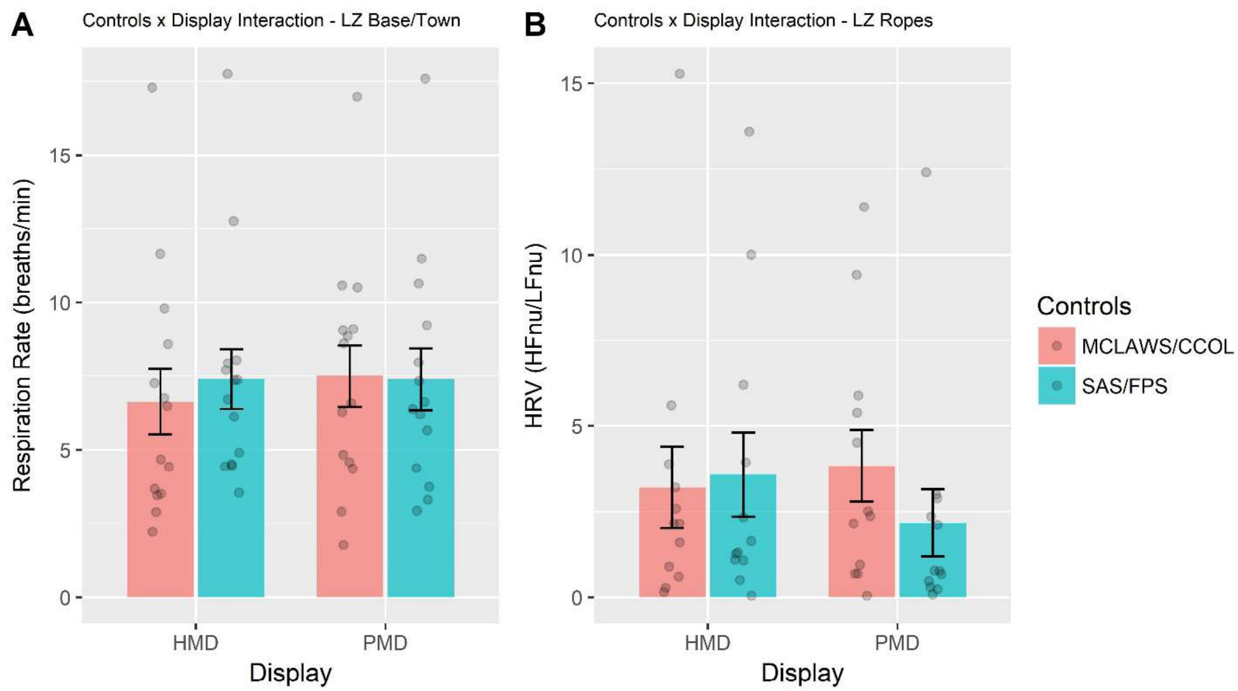


Figure 10. Controls x Display interactions for approach LZ Base/Town respiration rate (A) and LZ Ropes HRV (B). Bars represent means, dots represent individual observations, and error bars represent ± 1 standard error of the mean.

Eye Gaze Approach through Landing / End of Hover

The mean percentages of fixations in each AOI during the approach segment across all pilots, landing zones, and control types are shown in Figures 11 and 12. Eye gaze heat maps for Symbology Sets A and B during the approach phase are displayed in Figures E8 and E9, respectively, in Appendix E.

Symbology Set A Approach

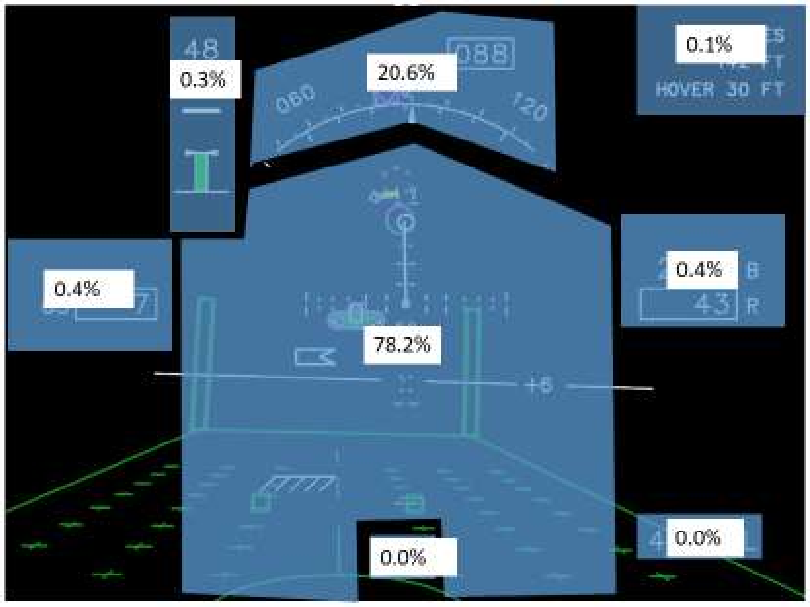


Figure 11. Symbology set A approach.

Symbology Set B Approach

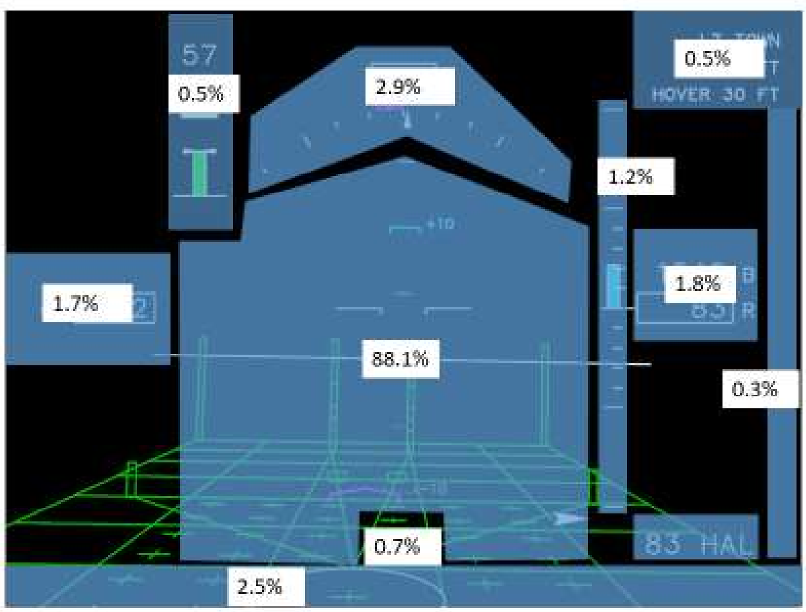


Figure 12. Symbology Set B approach.

Statistical tests were performed for 4 areas of interest of concern for system designers: altitude, center of PMD, heading, and speed. Means, standard errors, and *F* statistics for the approach eye gaze fixation percentages in each AOI (Altitude, Center of PMD, Heading and Speed) are displayed in Tables 6 and 7. The Altitude AOI showed higher percentage fixations for Symbology Set B than A for all LZs with LZ Town, Envoy and Base being statistically significant. The Center of the PMD AOI showed higher fixations for Symbology Set B than Symbology Set A for LZ Town and LZ Base while the effect was opposite, and smaller, for LZ Envoy. The Heading AOI showed much higher percentage fixations for Symbology Set A than Symbology Set B across all LZs. The Speed AOI showed higher percentage fixations for Symbology Set B than Symbology Set A for all LZs with LZ Envoy, Base, and Ropes being statistically significant. Only the Heading AOI showed statistically significant differences for the effect of control type for LZ Town, Envoy, and Ropes.

Table 6. Approach Eye Gaze Proportions for the Main Effect of Symbology Set

	Symbology Set A		Symbology Set B				
	M	*SE*	*M*	*SE*	*F*	*p*	η_p^2
Town							
Altitude AOI	.0007	.0005	.0097	.0034	5.903	.045	.457
Center of PMD AOI	.3790	.0739	.8132	.0245	20.006	.003	.741
Heading AOI	.2475	.0567	.0149	.0087	12.731	.009	.645
Speed AOI	.0042	.0019	.0113	.0031	2.876	.134	.291
Envoy							
Altitude AOI	.0038	.0018	.0102	.0033	2.176	.184	.237
Center of PMD AOI	.6673	.0557	.4365	.0567	6.903	.034	.497
Heading AOI	.1171	.0345	.0263	.0134	11.183	.012	.615
Speed AOI	.0014	.0005	.0069	.0018	8.934	.020	.561
Base							
Altitude AOI	.0032	.0029	.0096	.0031	6.362	.040	.476
Center of PMD AOI	.3583	.0747	.7372	.0494	14.321	.007	.672
Heading AOI	.1418	.0457	.0154	.0079	6.073	.043	.465
Speed AOI	.0022	.0014	.0162	.0046	14.723	.006	.678
Ropes							
Altitude AOI	.0017	.0008	.0129	.0045	7.432	.029	.515
Center of PMD AOI	.5530	.0764	.6346	.0648	.535	.488	.071
Heading AOI	.1556	.0290	.0248	.0131	18.095	.004	.721
Speed AOI	.0021	.0009	.0129	.0045	8.681	.022	.554

Table 7. Approach Eye Gaze Proportions for the Main Effect of Control Type

	SAS/FPS		MCLAWS/CCOL				
	M	*SE*	*M*	*SE*	*F*	*p*	η_p^2
Town							
Heading AOI	.0739	.0260	.1885	.0631	13.499	.008	.659
Envoy							
Heading AOI	.1024	.0387	.0457	.0143	5.724	.048	.45
Base							
Heading AOI	.0746	.0248	.0916	.0507	.066	.805	.009
Ropes							
Heading AOI	.0387	.0146	.1331	.0316	10.433	.014	.598

Hover Performance

Symbology set had a significant effect on heading deviation during LZ Ropes and radial error during LZs Envoy and Ropes. As with the previous effects of symbol set, Symbology Set A had superior performance compared to Symbology Set B (See Table F2, Appendix F). Moreover, there was a significant symbol set by controls interaction for altitude deviations during LZ Ropes, $F(1, 5) = 18.92$, $p = .007$, $\eta_p^2 = .79$. No significant differences in altitude hold performance between control types were observed when Symbology Set A was used. However, MCLAWS/CCOL ($M = 2.22$, $SE = 0.12$) significantly improved altitude deviations compared to SAS/FPS ($M = 7.38$, $SE = 1.21$) controls when Symbology Set B was used. There was also a significant controls by display interaction for altitude deviations during LZ Ropes, $F(1, 5) = 9.67$, $p = .027$, $\eta_p^2 = .66$. No significant differences in attitude hold performance between control types were found when the HMD was used. When the PMD was used, participants performed better with MCLAWS/CCOL ($M = 2.39$, $SE = 0.275$) compared to SAS/FPS ($M = 6.04$, $SE = 1.07$). These interactions are displayed in Figure 13 below.

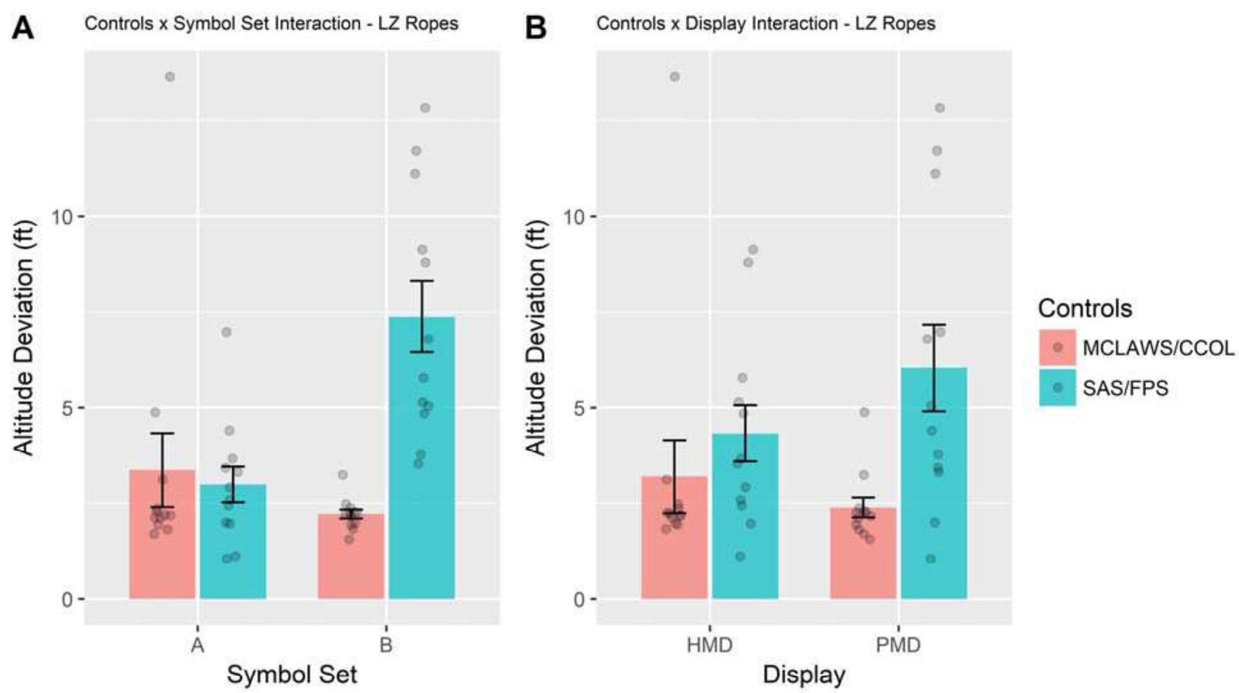


Figure 13. Symbology Set x Controls interaction for LZ Ropes hover altitude deviations (A). Controls x Display Interaction for LZ Ropes hover altitude deviations (B). Bars represent means, dots represent individual observations, and error bars represent ± 1 standard error of the mean.

Hover Biometrics

Biometric data for hover performance was only collected at LZ Envoy due to a short duration hover at LZ Ropes. A significant three-way interaction was found for respiration rate, $F(1, 5) = 12.692$, $p = 0.016$, $\eta_p^2 = 0.72$ (See Figure 14). A significant main effect of display was also found for the EEG workload index, $F(1, 7) = 6.60$, $p = 0.037$, $\eta_p^2 = 0.49$. Workload index values were higher when PMD ($M = 0.84$, $SE = 0.02$) was used compared to HMD ($M = 0.82$, SE

= 0.01). Additionally, a significant main effect of Controls was found for the EEG engagement index, $F(1, 7) = 6.95$, $p = 0.03$, $\eta_p^2 = 0.50$. Pilots were more engaged when flying with MCLAWS/CCOL ($M = 0.69$, $SE = 0.05$) compared to SAS/FPS ($M = 0.63$, $SE = 0.04$). Full results for main effects are in Table G6, Appendix G.

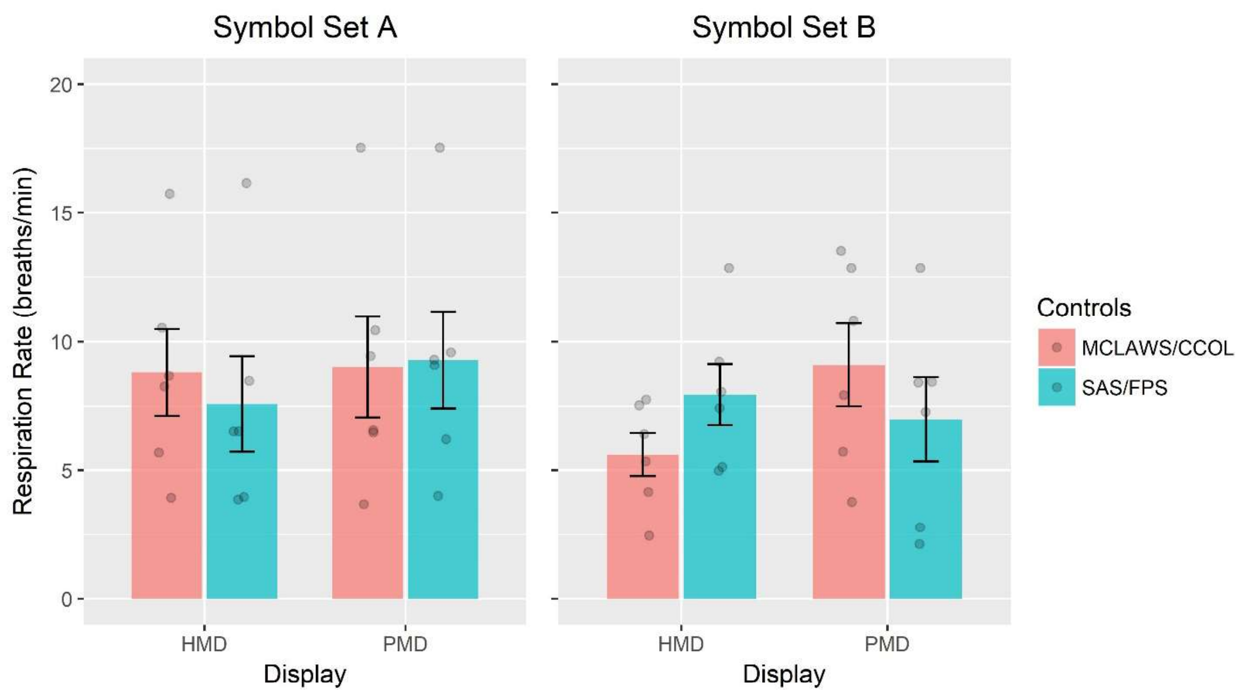


Figure 14. Symbology Set x Controls x Display interaction for LZ Envoy hover respiration rate. Bars represent means, dots represent individual observations, and error bars represent +/- 1 standard error of the mean.

Landing Performance

For landing performance, symbol set significantly affected radial error and touchdown lateral speed at all landing LZs (see Table F3, Appendix F). In each case, participants had less radial error from the desired touchdown point and slower lateral speeds at touchdown with Symbology Set A compared to Symbology Set B. Visual representations of landing positions at touchdown for the LZs are displayed in Figure 15.

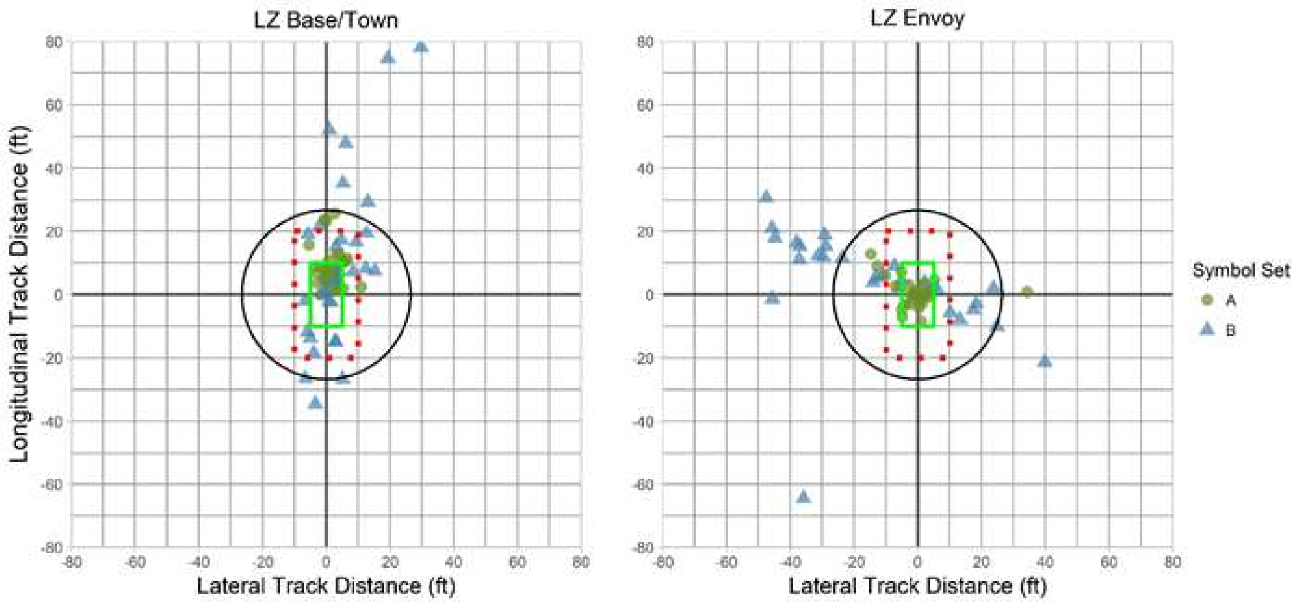


Figure 15. Landing position performance for LZ Base/Town (left) and LZ Envoy (right) by symbology set.

Note. ○ = Rotor Blade Diameter; ----- = Adequate; —— = Ideal. Landing positions were determined by the aircraft's center of gravity, which sat approximately below the main rotor blade shaft.

Three significant interactions for landing performance were also found. A significant controls by display interaction was found for LZ Base/Town touchdown lateral speed, $F(1, 7) = 10.19$, $p = .015$, $\eta_p^2 = .59$. No significant follow up tests were found; however, when SAS/FPS controls were used, participants had marginally slower lateral speeds with the HMD ($M = 0.20$, $SE = 0.03$) compared to the PMD ($M = 0.53$, $SE = 0.15$). No significant differences were found when MCLAWS/CCOL was used (see Figure 16). A significant symbology set by display interaction was also found for LZ Base/Town landing heading deviations, $F(1, 7) = 11.81$, $p = .011$, $\eta_p^2 = .59$. When the HMD was used, there were no significant differences between the symbology sets. When the PMD was used, Symbology Set A ($M = 1.95$, $SE = 0.31$) had significantly less heading deviation at touchdown than Symbology Set B ($M = 5.14$, $SE = 0.80$). This interaction is displayed in Figure 4. Finally, there was a significant controls by display interaction for LZ Envoy heading deviation, $F(1, 6) = 7.18$, $p = .037$, $\eta_p^2 = .55$. No significant follow up tests were found; however, when SAS/FPS controls were used, participants had marginally less heading deviation with the PMD ($M = 2.48$, $SE = 0.55$) compared to the HMD ($M = 3.99$, $SE = 0.69$). No marginal differences were found when MCLAWS/CCOL was used (See Figure 16).

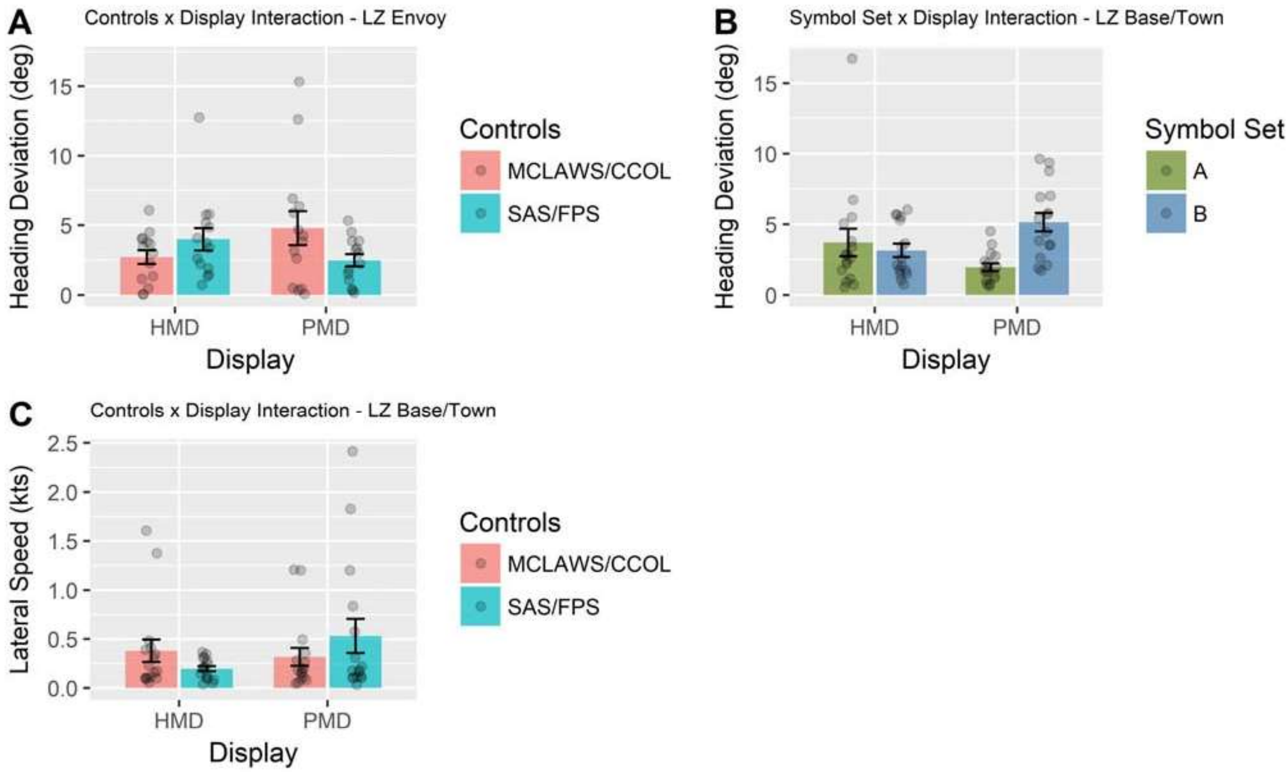


Figure 16. Controls x Display interaction for LZ Envoy landing heading deviations (A). Symbology set x Display Interaction for LZ Base/Town landing heading deviations (B). Controls x Display interaction for LZ Base/Town landing lateral speed (C). Bars represent means, dots represent individual observations, and error bars represent +/- 1 standard error of the mean.

Subjective Results

Training Questionnaire.

The seven training effectiveness questions were aggregated into percentages for each response option and each symbology type (Set A and Set B) and are presented in Figure 17 below. The vast majority of training questionnaire responses were positive with either “agree” or “strongly agree” responses. A Wilcoxon signed rank test indicated that ratings of training effectiveness were not different between Symbology Set A (M = 4.46, SD = 0.42) and Symbology Set B (M = 4.30, SD = 0.43) conditions (Z = -0.171, p = .906). Comments were also gathered for the training questionnaire and are listed in Appendix H.

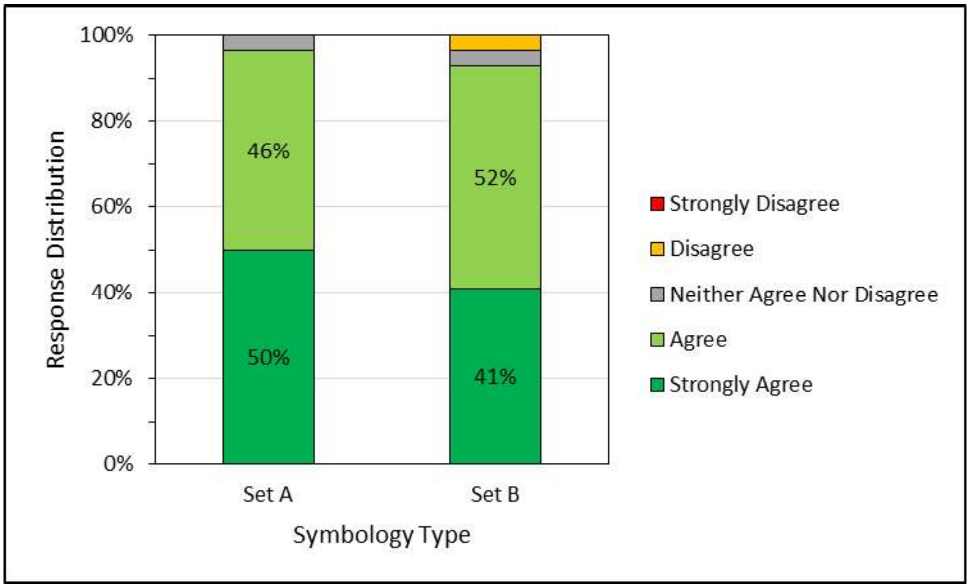


Figure 17. Training questionnaire response distribution for symbology type.

Motion Sickness Assessment Questionnaire.

A Wilcoxon signed rank test indicated that ratings of motion sickness were not different between PMD (M = 12.52, SD = 3.08) and HMD (M = 13.09, SD = 3.57) conditions (Z = -1.162, p = .245). It is worth noting that the reporting MSAQ scores are very low for both PMD and HMD conditions (MSAQ scores can range from 11.11 to 100). Pilots' comments were also collected with this measure, and are summarized in Appendix I.

Bedford Workload Ratings.

Workload rating response distributions were computed for each phase of flight and 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," respectively. The workload rating distribution for each independent variable: symbology type (Set A versus Set B), display type (HMD versus PMD), and flight control (SAS/FPS versus MCLAWS/CCOL) are presented in Figure 8, 19, and 20, respectively. Generally, the vast majority of workload ratings were in the "low" to "moderate" categories. Symbology Set B had more "high" workload ratings as compared to Symbology Set A, which had no "high" workload ratings. Pilots' comments were also collected with this measure, and are summarized in Appendix J.

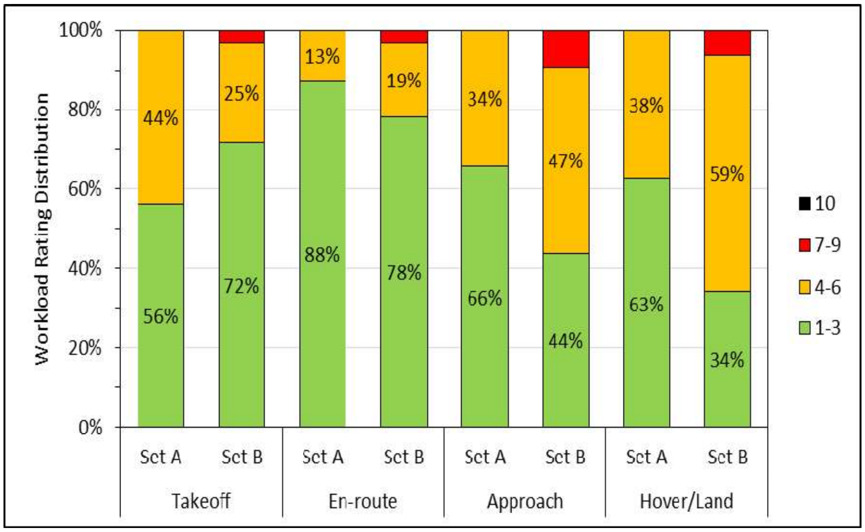


Figure 18. Workload rating distribution for symbology type.

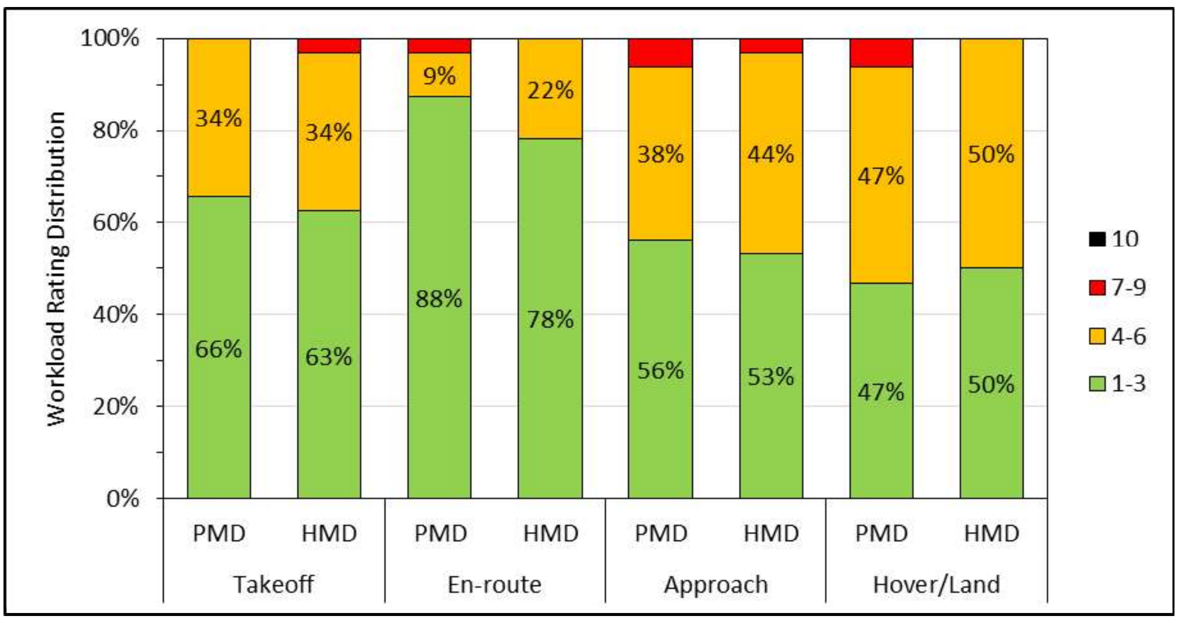


Figure 19. Workload rating distribution for display type.

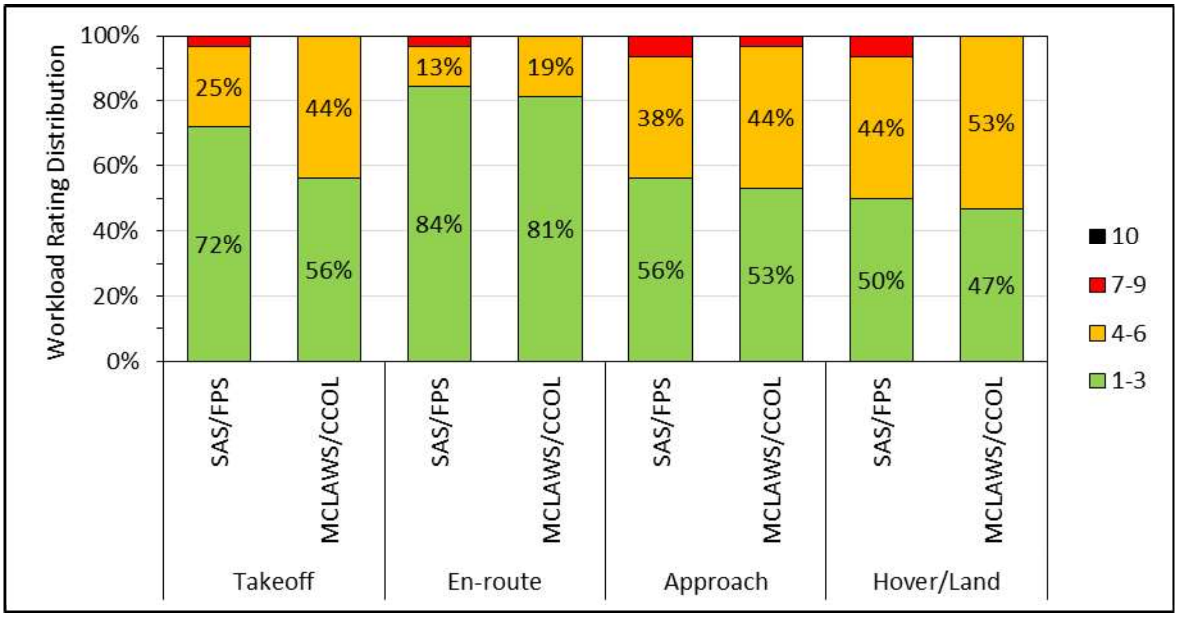


Figure 20. Workload rating distribution for flight control type.

Wilcoxon signed rank tests were computed for workload ratings by independent variable and phase of flight. Results of the Wilcoxon signed rank tests are summarized in Table J1, Appendix J. Workload ratings were significantly lower (better) for Symbology Set A during approach and hover, marginally lower during en-route, and were not significantly different during takeoff. There were no significant differences in workload ratings between display types (PMD versus HMD) or flight control types (SAS/FPS versus MCCLAWS/CCOL) during any phase of flight. Open-ended comments were also collected regarding workload. These were categorized as "General Workload," "Workload Relating to Symbology Set A," "Workload Relating to Symbology Set B," "Workload Relating to Flight Control Type," and "Workload Relating to Display Type" comments. A full list of comments can be found in Appendix J.

Situation Awareness Ratings.

Internal and external situation awareness rating response distributions were computed for each phase of flight and 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, respectively.

Internal SA.

Internal SA rating distributions for each independent variable: symbology type (Set A versus Set B), display type (HMD versus PMD), and flight control (SAS/FPS versus MCLAWS/CCOL) are presented in Figures 21, Figure 22, and 23, respectively. Generally, the vast majority of internal SA ratings were in the "high" to "moderate" categories. There were no "low" or "none" SA ratings across any condition.

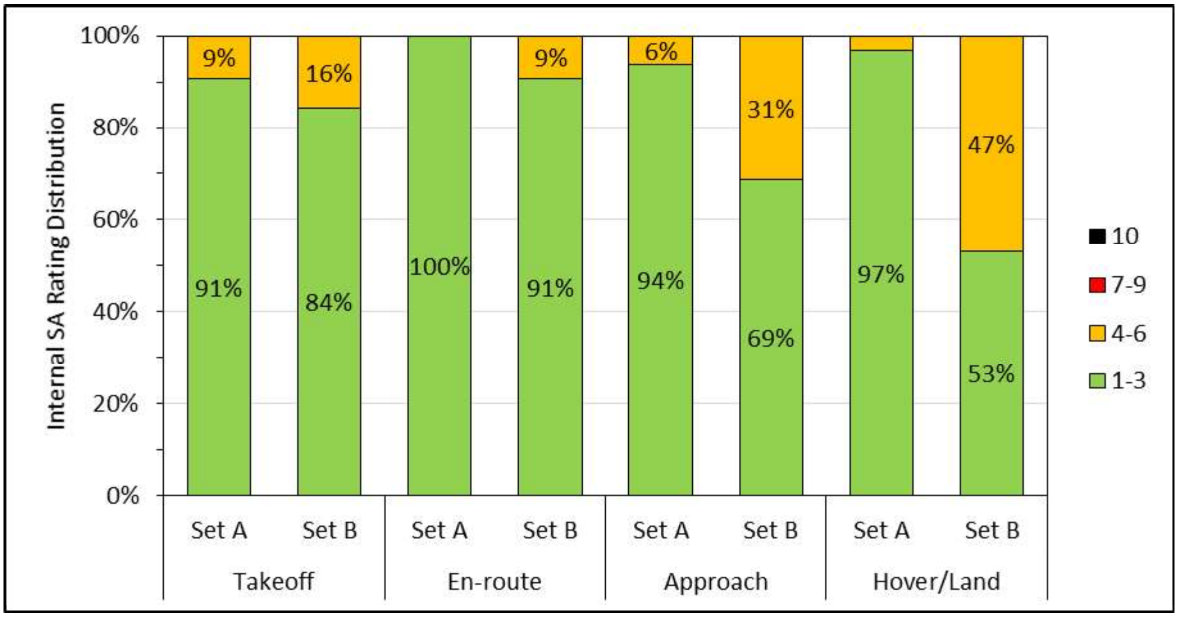


Figure 21. Internal SA rating distribution for symbology type.

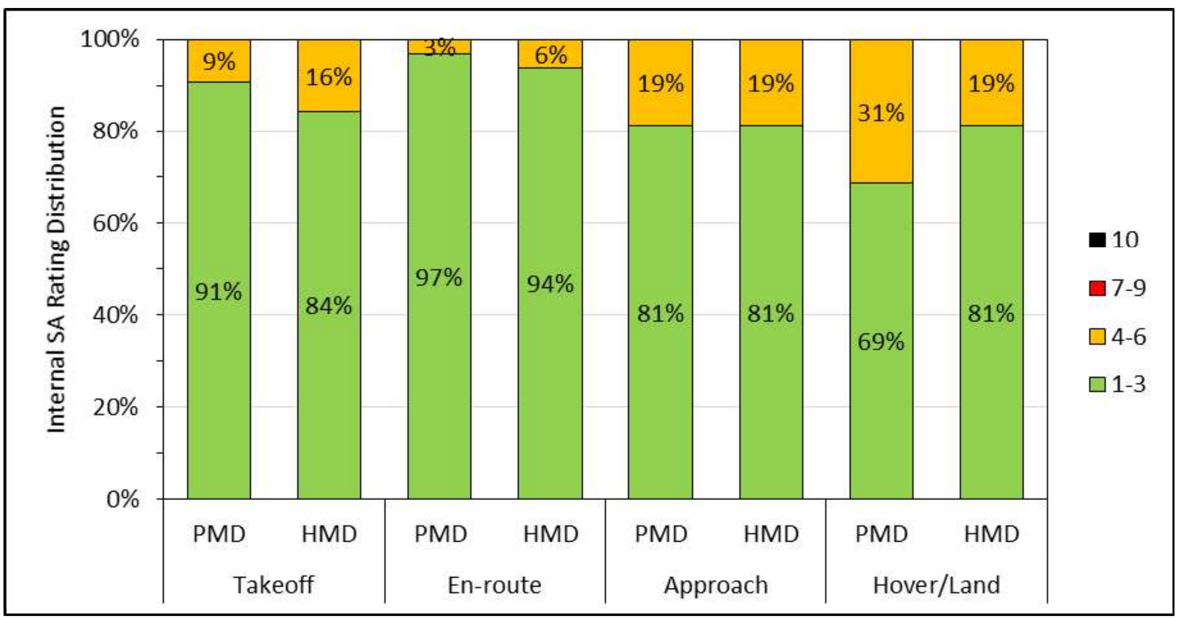


Figure 22. Internal SA rating distribution for display type.

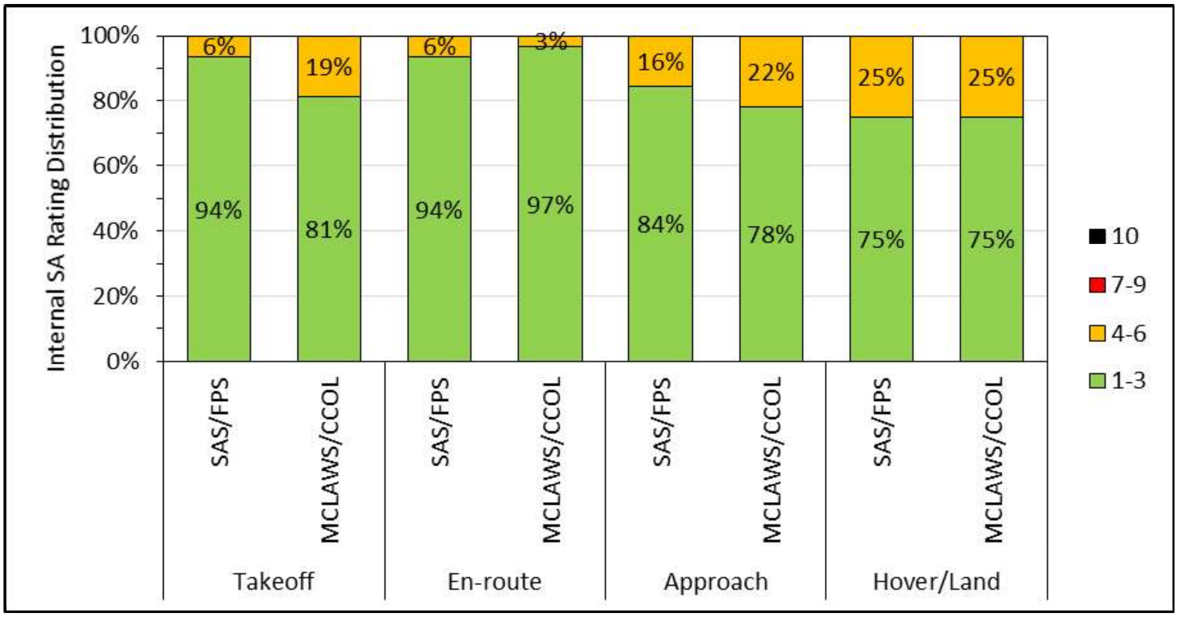


Figure 23. Internal SA rating distribution for flight control type.

Wilcoxon signed rank tests were computed for internal SA ratings by independent variable and phase of flight. Results of the Wilcoxon signed rank tests are summarized in Table K1 in Appendix K.

Internal SA ratings were significantly lower (better) for Symbology Set A during approach and hover, marginally lower en-route, and were not significantly different during takeoff. There were no significant differences in internal SA ratings between display types (PMD versus HMD) or flight control types (SAS/FPS versus MCCLAWS/CCOL) during any phase of flight. Open-ended comments were also collected and are reported in Appendix K.

External SA.

External SA rating distributions for each independent variable: symbology type (Set A versus Set B), display type (HMD versus PMD), and flight control (SAS/FPS versus MCLAWS/CCOL) are presented in Figures 24, 25, and 26, respectively. Generally, the vast majority of external SA ratings were in the “high” to “moderate” categories.

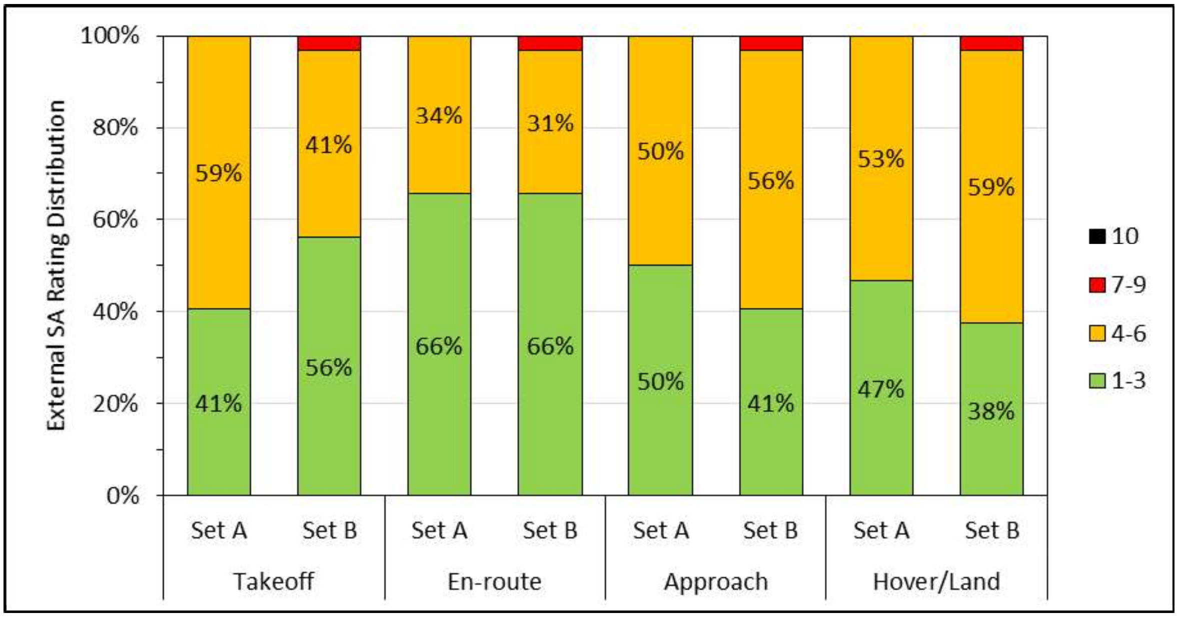


Figure 24. External SA rating distribution for symbology type.

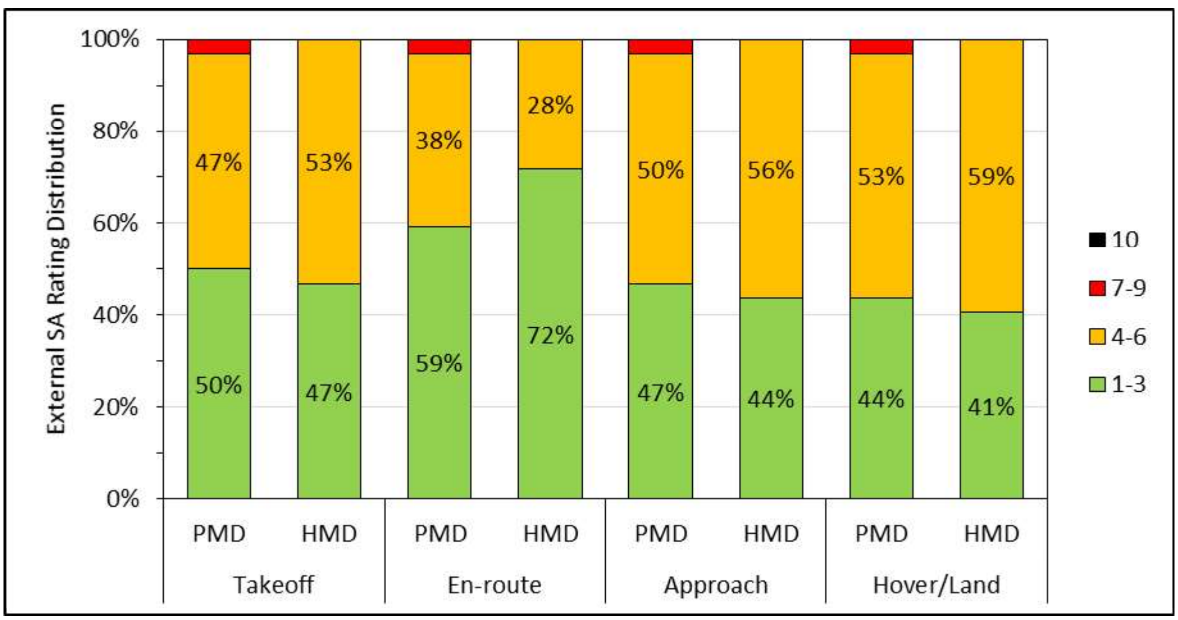


Figure 25. External SA rating distribution for display type.

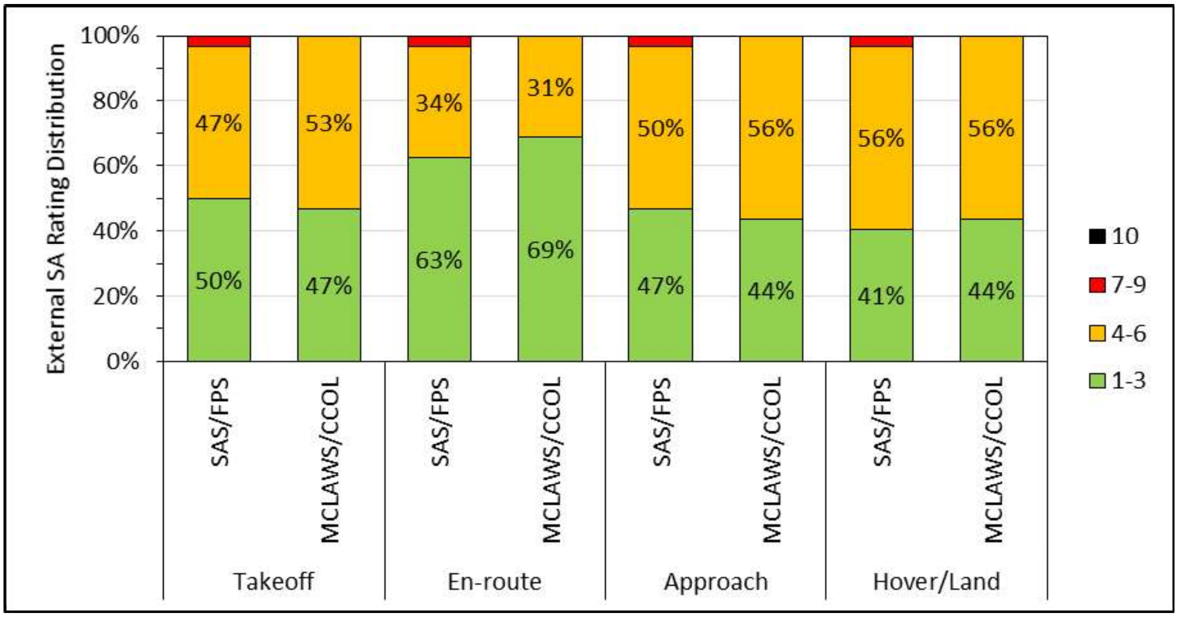


Figure 26. External SA rating distribution for flight control type.

Wilcoxon signed rank tests were computed for external SA ratings by independent variable and phase of flight. Results of the Wilcoxon signed rank tests are summarized in Table K2 in Appendix K. External SA ratings were marginally lower (better) for Symbology Set A during approach, and were not significantly different during takeoff, en-route, or hover. There were no significant differences in external SA ratings between display types (PMD versus HMD) or flight control types (SAS/FPS versus MCCLAWS/CCOL) during any phase of flight. Open-ended comments were also collected and are reported in Appendix K.

Cueing Usability Questionnaire.

Cueing usability response distributions were calculated for each symbology type (Set A and Set B) and for each cueing feature: 2D symbology, guidance symbology, 3D conformal symbology, sensor visualization, aural cueing, and tactile cueing. The cueing usability response distributions are presented below in Figures 27, 28, 29, 30, 31, and 32.

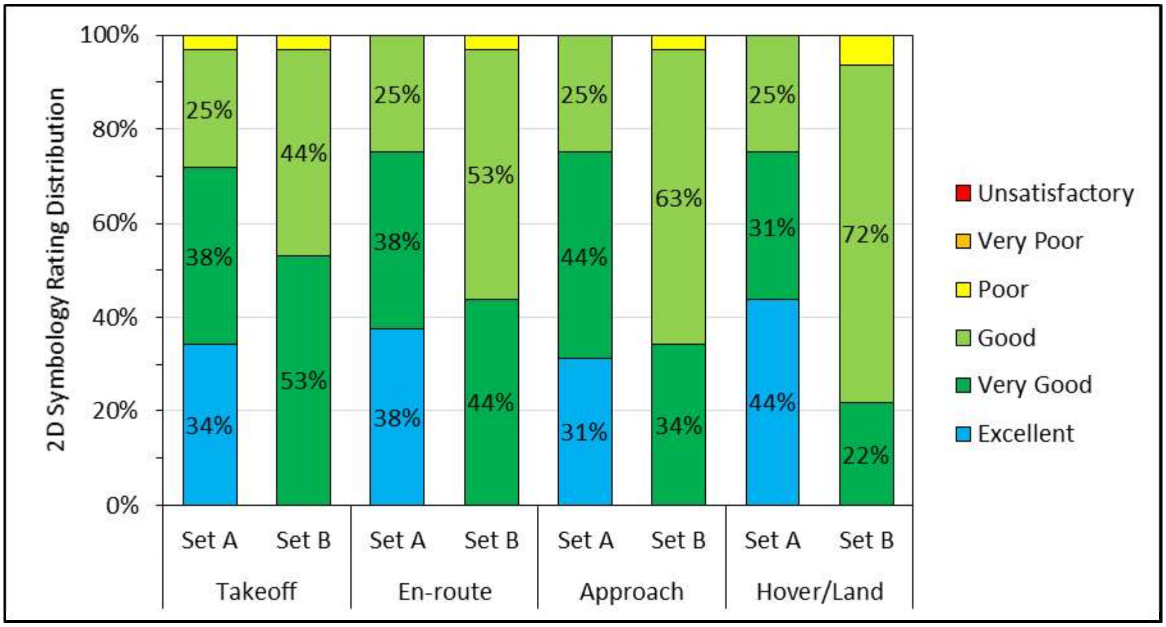


Figure 27. 2D symbology usability rating distribution for symbology type.

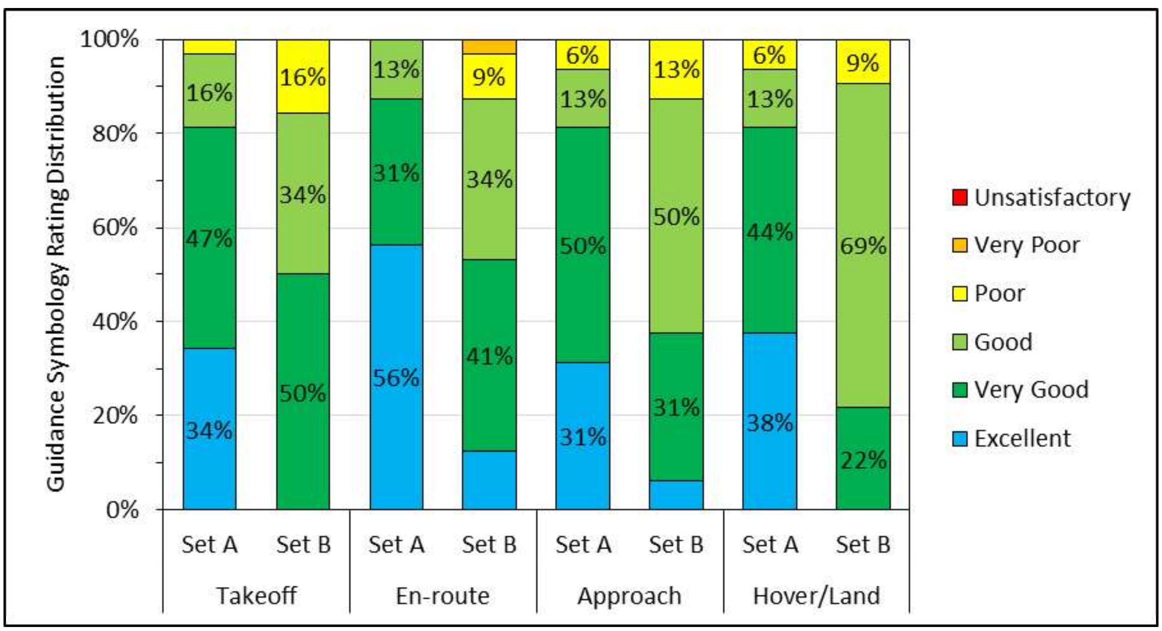


Figure 28. Guidance symbology usability rating distribution for symbology type.

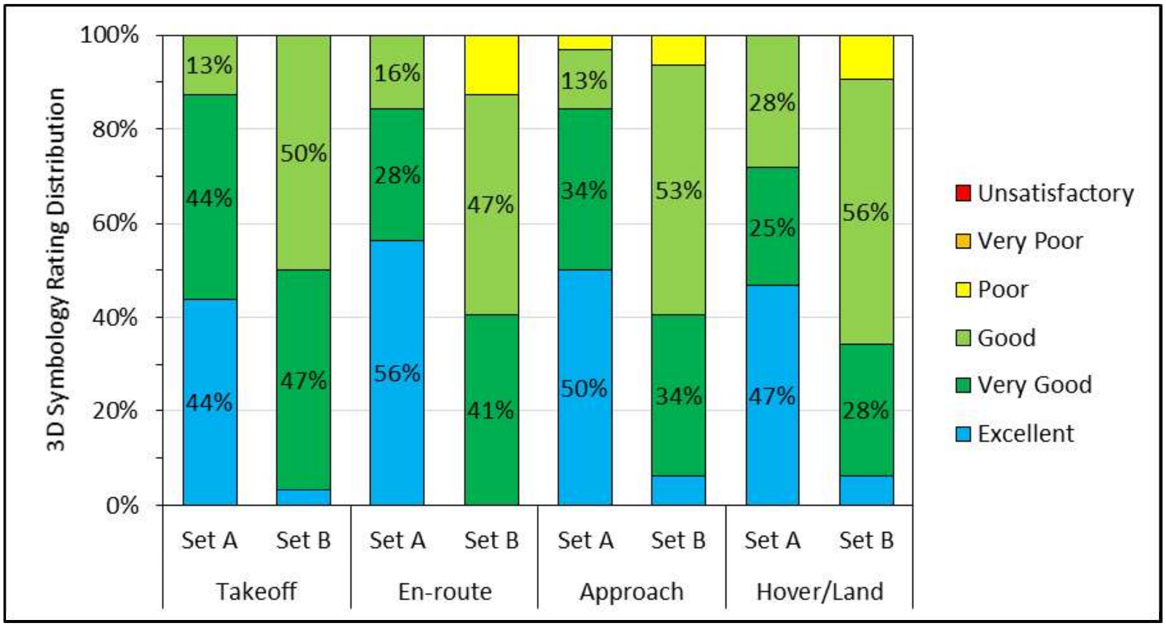


Figure 29. 3D symbology usability rating distribution for symbology type.

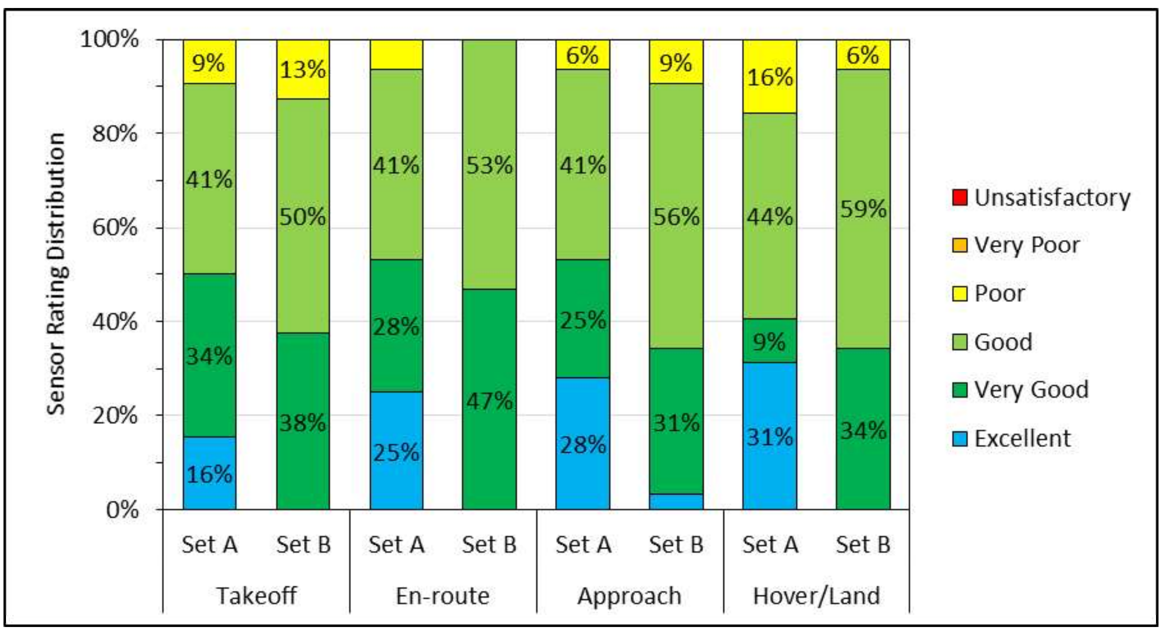


Figure 30. Sensor visualization usability rating distribution for symbology type.

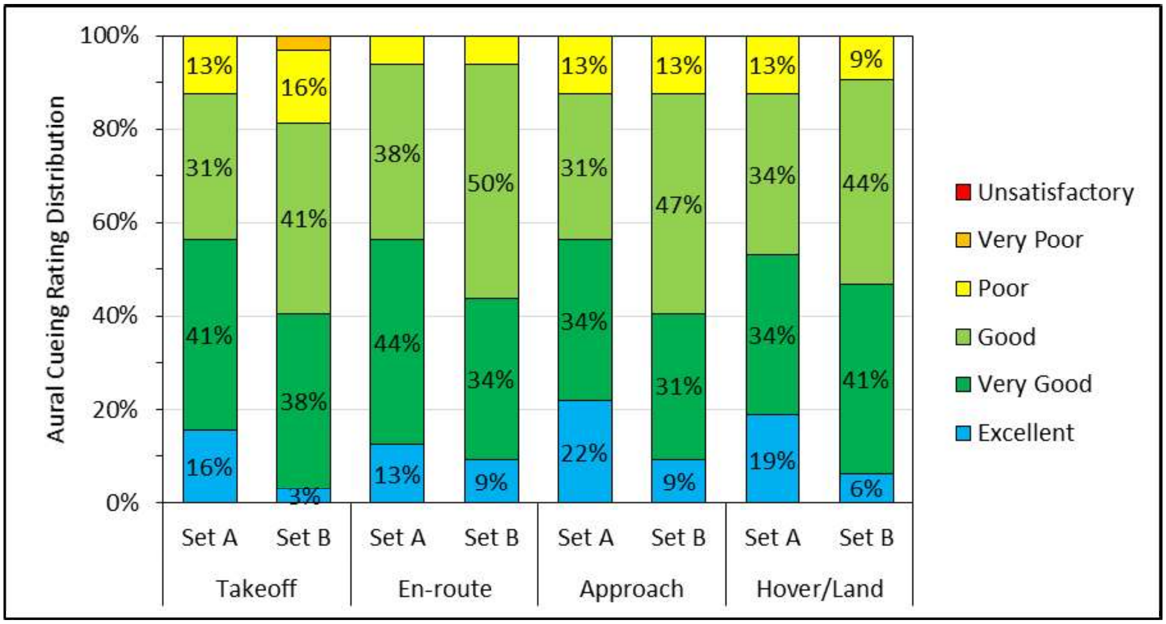


Figure 31. Aural cueing usability rating distribution for symbology type.

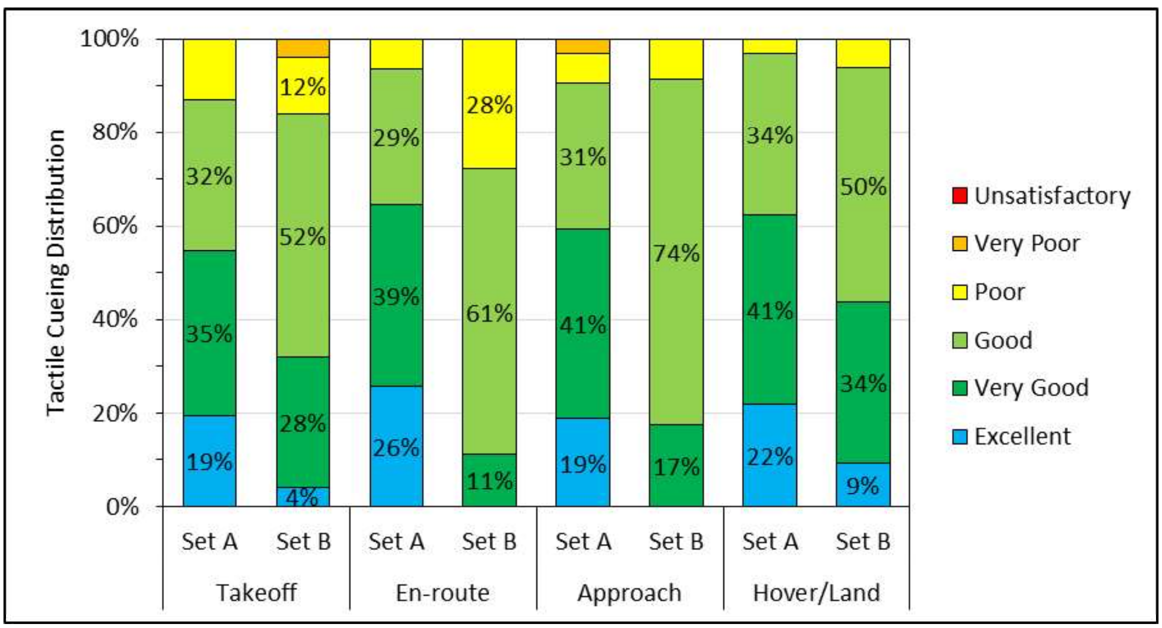


Figure 32. Tactile cueing usability rating distribution for symbology type.

Generally, the vast majority of usability ratings were positive for both Symbology Set A and Set B. There were no “unsatisfactory” usability ratings across any condition. Wilcoxon signed rank tests were computed for the usability ratings of each cueing feature and phase of flight. Results of the Wilcoxon signed rank tests are summarized in Table L1, Appendix L.

Response distributions were also calculated for subjective ratings of aircraft controllability by phase of flight for each flight control type (SAS/FPS versus MCLAWS/CCOL) and are presented in Figure 33. Wilcoxon signed rank tests were computed for the controllability ratings of each cueing feature and phase of flight. Results of the Wilcoxon signed rank tests are summarized in Table L2, Appendix L.

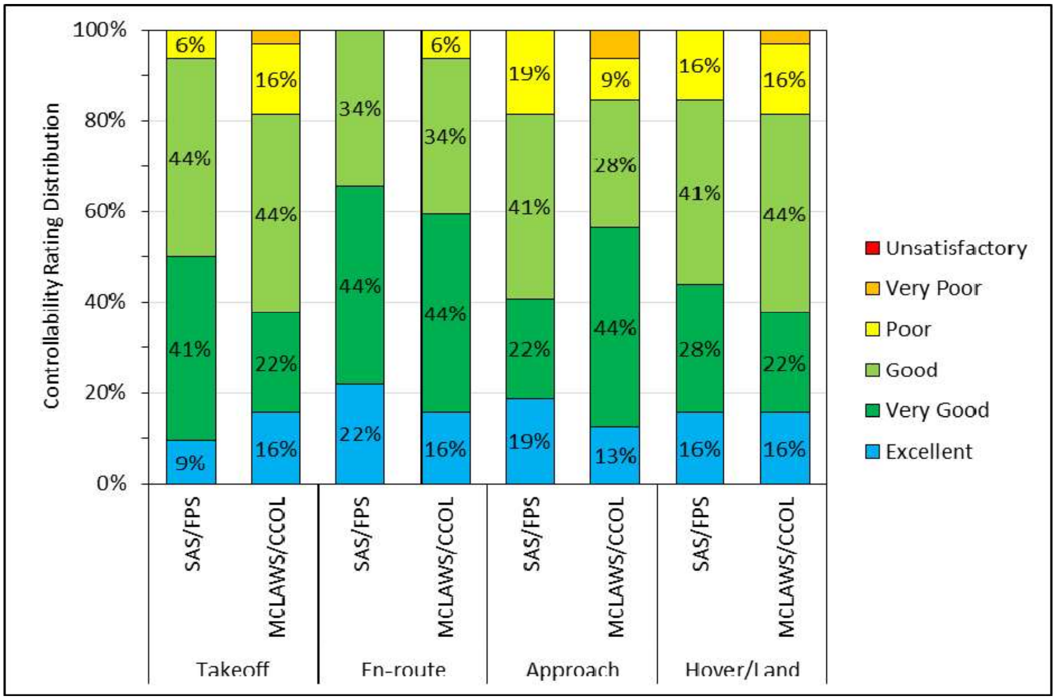


Figure 33. Aircraft controllability rating distribution for flight control type.

There were no significant differences in internal aircraft controllability ratings between flight control types (SAS/FPS versus MCLAWS/CCOL) during any phase of flight. Open-ended comments were also collected regarding cueing usability and are categorized by symbology type and phase of flight in Appendix L.

System Usability Scale.

SUS scores were computed for each symbology type and are presented as box and whisker plots in Figure 34.

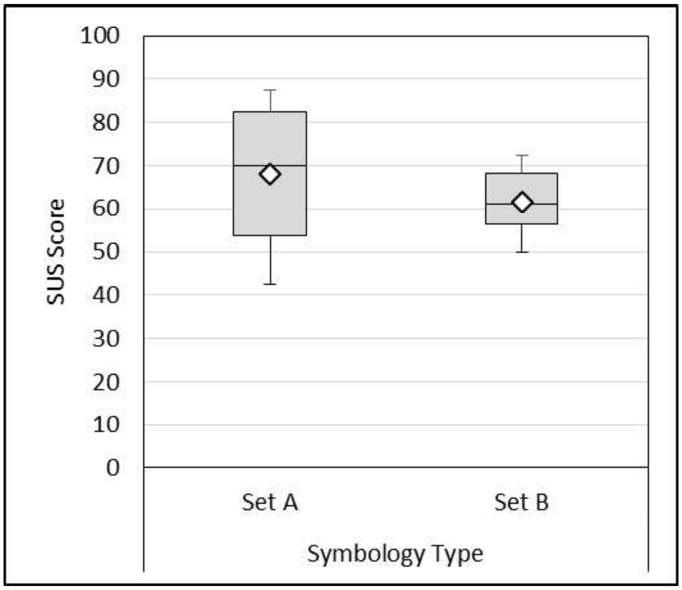


Figure 34. SUS scores for symbology type.

A Wilcoxon signed rank test indicated that SUS scores were not different between Symbology Set A (M = 68.125, SD = 15.68) and Symbology Set B (M = 61.563, SD = 7.31) conditions (Z = -1.018, p = .375).

Trust in Automation Questionnaire.

The four trust in automation questions were aggregated into percentages for each response option for cueing (Set A and Set B) and flight control & guidance algorithm (SAS/FPS and MCLAWS/CCOL) and are presented in Figures 35 and 36, respectively. The majority of the trust in automation questionnaire responses were positive with either "agree" or "strongly agree" responses.

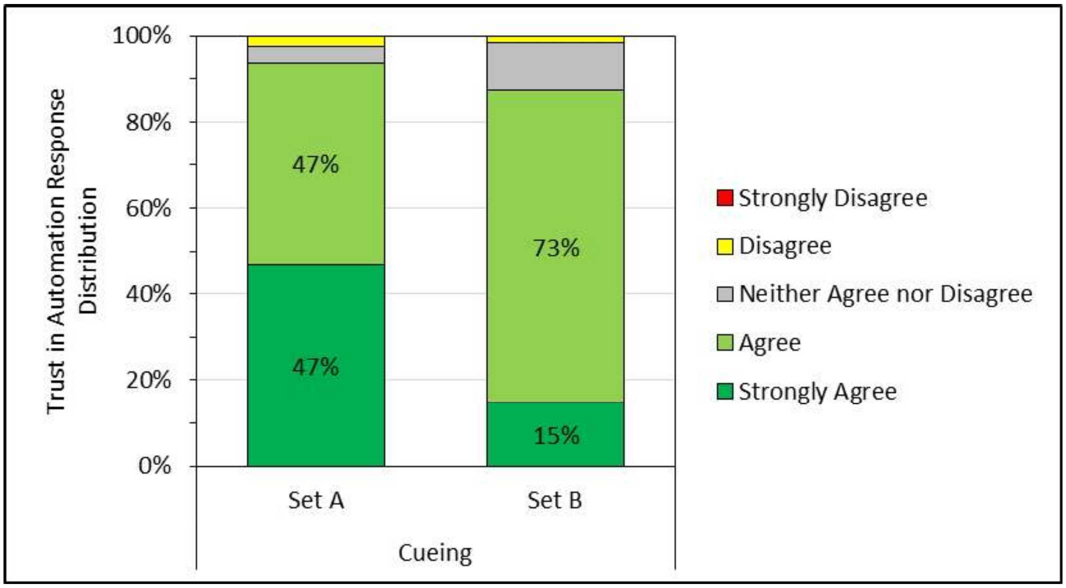


Figure 35. Trust in automation (cueing) response distribution for symbology type.

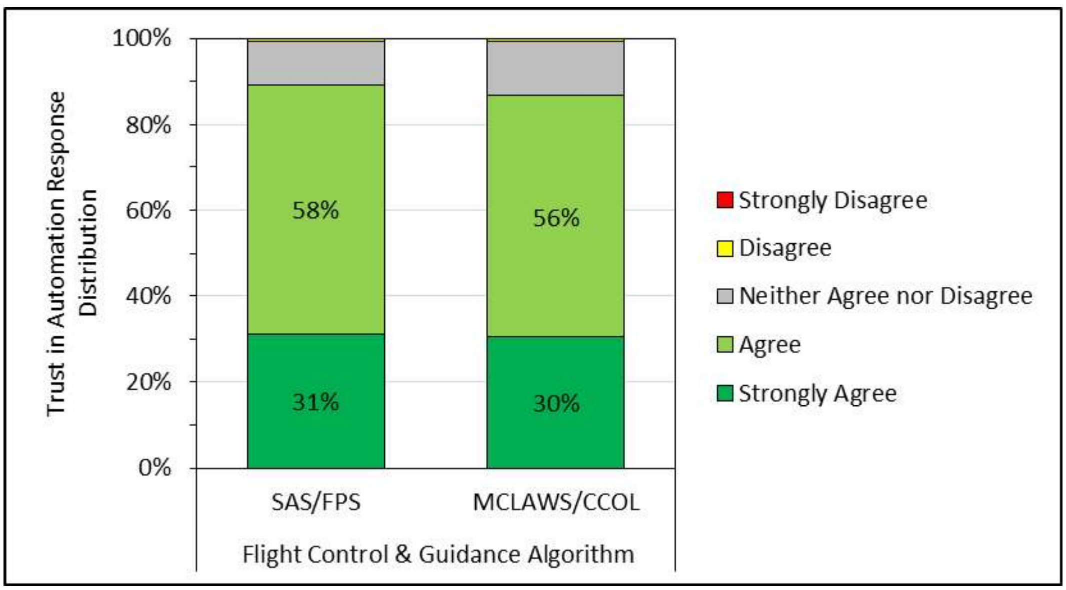


Figure 36. Trust in automation (flight control & guidance algorithm) response distribution for flight control type.

A Wilcoxon signed rank test indicated that mean ratings of cueing trust in automation for symbology type was significantly higher (better) for Symbology Set A (M = 4.38, SD = 0.55) than Symbology Set B (M = 4.01, SD = 0.39) conditions (Z = -3.160, p = .001). A Wilcoxon signed rank test indicated that there was no difference in mean ratings of flight control & guidance algorithm trust in automation for flight control type for SAS/FPS (M = 4.20, SD = 0.49) versus MCLAWS/CCOL (M = 4.16, SD = 0.56) conditions (Z = -0.810, p = .450). Open-ended comments were also collected and are in Appendix M.

Overall Preference Questionnaire.

Overall preferences were tallied by phase of flight for symbology type, display type, and flight control mode and are summarized in

Table 88. The counts in each cell represent pilots, e.g. A > B should be interpreted as 5 versus 3, indicating that five pilots preferred Symbology Set A versus three pilots that preferred Symbology Set B.

Pilots preferred Symbology Set A versus Symbology Set B in the takeoff, approach, and hover phase. Pilots exhibited split preference for symbology during the en-route phase. Pilots preferred the HMD versus the PMD in all phases of flight except en-route. Pilots preferred SAS/FPS flight control mode versus MCLAWS/CCOL in all phases of flight except approach.

Table 8. Overall Preferences by phase of Flight (Pilot Count)

	Flight Phase			
	Takeoff	En-route	Approach	Hover
Symbology (Set A versus Set B)	**A > B** 5 vs. 3	**A = B** 4 vs. 4	**A > B** 5 vs. 3	**A > B** 6 vs. 2
Display Type (PMD versus HMD*)*	**P < H** 2 vs. 6	**P > H** 5 vs. 3	**P < H** 2 vs. 6	**P < H** 3 vs. 5
Flight Control Mode *(*SAS/FPS versus MCLAWS/CCOL)	**S > M** 5 vs. 3	**S > M** 5 vs. 3	**S < M** 3 vs. 5	**S > M** 5 vs. 3

Pilots were also asked to indicate their prioritization of task performance, workload, and situation awareness for each phase of flight. Responses indicated that the majority of pilots considered task performance the priority for all phases of flight, except en-route, where situation awareness was the priority.

Discussion

Crashes

Noteworthy is that 8 of the 11 crashes occurred using Symbology Set B, and 7 of the 11 crashes occurred while MCLAWS/CCOL were used.

Performance

Results from performance data indicate that, overall, symbology set had the most consistent effects on flight performance. Symbology Set A resulted in better performance on a majority of flight performance metrics across LZs than Symbology Set B. More predominant improvements in performance resulting from using Symbology Set A were observed during landing and en-route phases of flight. Moreover, when symbology set interacted with another factor (e.g., controls) Symbology Set B often resulted in worse performance for one level of the other interacting factor. In other words, Symbology Set A produced relatively consistent flight performance even with different control and display configurations. Also, Symbology Set A generally resulted in less flight performance metric variability overall. This is the most evident in the landing position performance plots displayed in Figure 3. Participants were more consistent and precise landing with Symbology Set A compared to Symbology Set B.

Other results concerning the effects of controls and display should be interpreted with caution as they are less consistent than the effects of symbology set. Given the limited number of subjects in this study and the number of variables included, the effects of controls and display should be considered preliminary. The effects of controls and display on flight performance were mostly apparent when Symbology Set B was used. Only one main effect (approach speed deviation) and one interaction, controls by display interaction, with significant comparisons (hover altitude deviation) were found, making it difficult to draw specific conclusions about the effects of the different displays and controls on flight performance. Additionally, the qualitatively different structure of the LZs likely changed how participants performed with the different control and display configurations and thus limits a general conclusion on these features. While the SAS/FPS controls combined with PMD might be beneficial for a pinnacle landing, the SAS/FPS controls combined with HMD may be beneficial for a normal landing. Overall, however, Symbology Set A resulted in better and more stable flight performance than Symbology Set B.

Biometrics

Results from the biometric data generally followed the same patterns as the performance data, where overall Symbology Set A resulted in lowered workload metrics compared to Symbology Set B. These lower metrics were quantified with interactions, as no main effect of symbol set was found. Patterns included lowered respiration rates, EEG indices, and HRV. These suggest that Symbology Set A allowed pilots to more efficiently manage their cognitive workload. However, it should be noted that overall all conditions produced relatively large physiological responses in terms of workload. This was expected, as this group of pilots were exposed to new symbology sets, cueing, and flight controls and were asked to learn these rather quickly and then perform simulated flights. However, the differences seen in workload suggest that Symbology Set A may be easier for pilots to integrate and learn, and that both sets appear to be more readily integrated when displayed on HMD compared to PMD.

Additionally, biometric data supported that the MCLAWS/CCOL flight controls configurations tended to produce an increased workload, but again this is likely due to the amount of information the pilots were learning and integrating during participation in this study. This finding may also be further explained by participants engaging in compensatory actions, where (at times) they neglected performance on the flight controls in order to maintain awareness of visual symbology. In other words, as flight demands increased, participants adapted flight strategies that prioritized one flight performance aspect (e.g., speed), while deprioritizing others (e.g., altitude) to maintain a constant level of cognitive effort. Previous work has shown that individuals will oftentimes engage in what is known as a “performance protection” strategy, where when faced with cognitively demanding tasks they will neglect performance on a subtask (e.g., controls) in order to maintain performance on a higher priority task (e.g., visual symbology) (Hockey, 1997; Hockey, 2011). Additionally, when they are under stress, operators may also engage in compensatory efforts to preserve task performance, but at the expense of increased energy costs. The novelty of the MCLAWS/CCOL control system combined with new ICE symbology and cueing may have required participants to increase effort in order to maintain adequate task performance. This increased effort may have resulted in a physiological cost revealed through elevated biometric responses. Increased training would likely reduce this response.

Subjective and Ratings and Comments

Overall, the subjective measures followed the same patterns as found in performance in biometric data. Specifically, participants tended to rate workload lower for Symbology Set A, which agrees with the enhancement of performance on flights using Symbology Set A as well as the lower physiological response to workload. Further, analyses of subjective workload found that the largest improvements in workload occurred during approach and hover phases. SA ratings were similar, where Symbology Set A resulted in better SA.

In regards to usability, pilots rated Symbology Set A as more usable, and this was evident across all phases of flight. Sensor visualization usability ratings for Symbology Set A were significantly better than Symbology Set B in the approach phase only. Aural cueing usability ratings for Symbology Set A were significantly better than Symbology Set B in the takeoff phase only. Finally, tactile cueing usability ratings were significantly better for Symbology set A than Set B during all phases of flight. In their final questionnaire after all test flights had been completed, pilots indicated preference for Symbology Set A versus Set B in the takeoff, approach, and hover phase but were split during the en-route flight phase. Pilots indicated preference for the HMD versus the PMD in all phases of flight except en-route. Finally, pilots preferred SAS/FPS flight control mode versus MCLAWS/CCOL in all phases of flight except approach.

Visual Gaze

During the en-route portion of flight, pilots spent less time monitoring readouts for altitude in Symbology Set A than in Symbology Set B (1.9% versus 3.7% of the time, respectively). Although this difference was only significant during the en-route phase of LZ Town, in addition to this AOI, pilots in Symbology Set B spent 6.0% of their time monitoring the vertical course indicator. Combining these, pilots flying Symbology Set B spent 9.7% of their time looking away from the center of the PMD in order to monitor vertical height along the course compared to only 1.9% for Symbology Set A. This most likely indicates that the highway in the sky combined with the flight path marker allowed for easier vertical course monitoring by integrating this information in the center of the display.

Symbology Set B introduced a speed aerotape to the flight path marker in an attempt to address experimental test pilot concerns relative to the difficulty of monitoring the wings up/wings down speed indication used in Symbolology Set A. The differences between the amount of time spent looking at the actual speed readout were small (6.1% vs 5.6% en-route) and not statistically significant, possibly indicating that the speed information gleaned from these symbols was similar. Alternatively, the route may have been structured such that this information did not need to be referenced often. Additional study of a route with highly varying speed would help to further investigate any possible differences.

Symbology Set A showed much larger fixation proportions on the heading during the approach phase of flight. Qualitative analysis of flight video shows that pilots were fixating on the target horizontal speed "cup," which transitions through the heading indicator and that very little time was spent looking at the actual heading readout or indicator.

Symbology Set B showed larger fixation proportions on the altitude and speed AOIs during the approach phase of flight. Symbology Set A provided horizontal and vertical guidance cues that allowed pilots to immediately understand if altitude and speed were appropriate for the approach, while Symbology Set B required visual judgement of closure rates to the LZ with crosschecks to the radar altitude and ground speed readouts. Further study would be needed to determine if the increased fixations in these AOIs for Symbology Set B were needed due to a lack of necessary information or if these were simply due to the lessened demand for fixations on the horizontal and vertical speed cues found in Symbology Set A.

Limitations

Although the three independent variables manipulated in this study were included to comprehensibly test new system configurations, the large number of experimental conditions makes the interpretation of several interactive results difficult and less refined. Because several of the interactions changed (i.e., were significant during some LZs but not others), we were forced to make general conclusions about the effects of certain system configurations on overall performance. Although potentially limiting, valuable general conclusions were obtained for use in further system testing. Future testing of this system might benefit from an iterative testing process, where further refinements to the system are done sequentially (or with only two improvements) to maximize result interpretability. From the results presented here, it is recommended that further refinements to the system should build upon Symbology Set A. Given the low statistical power of this study, further testing is needed with more participants and a smaller factorial design to clarify any additional performance enhancements different control and display configurations provide with Symbology Set A.

Conclusions

An experiment was conducted to determine the efficacy of different types of multi-modal cueing to assist pilots during flight in DVE. Haptic and aural cueing, symbology displayed on either a HMD or PMD and advanced flight control laws for pilotage in DVE conditions were assessed. Eight pilots rated in the UH-60 Black Hawk performed several flight tasks in a simulator to evaluate the multi-modal cueing. The study was comparative in nature with pilots evaluating (1) a refined version of previous haptic, aural, and symbology cueing to an alternate version, (2) advanced flight laws to UH-60 flight control laws, and (3) usability of symbology on an HMD compared to a PMD.

Objective measures were pilot performance and biometric response during flight tasks. Subjective measures were pilot ratings for workload, SA and system usability. An additional workload and usability metric was eye tracking, which gave useful data on visual gaze, fixation, and pilot distraction.

Two sets of symbology were assessed for visual cueing during flight in DVE. Symbology Set A provided a high level of cueing information to pilots during flight in DVE and symbology Set B provided significantly less cueing symbology. Symbology Set A outperformed B in almost all phases of flight and in almost all metrics. Haptic and aural cues associated with Symbology Set A were significantly preferred by pilots compared to Set B.

Pilots preferred using the HMD compared to the PMD most of the time and commented that they had difficulty with the advanced control laws. Although the advanced flight control laws produced superior performance during approach and hover flight tasks, the pilots found the system harder to use. Biometric data confirmed that they were working harder when using these advanced control laws. This may have been due to lack of pilot experience using the advanced flight control laws. The pilots reported that they became more confident in their use throughout the experiment.

References

Berka, C., Levendowski, D. J., Lumicao, M. N., Yau, A., Davis, G., … & Craven, P. L. (2007). EEG correlates of task engagement and mental workload in vigilance, learning, and memory tasks. *Aviation, Space, and Environmental Medicine, 78*(5), B231-B244.

Brooke, J. (1996). SUS: A quick and dirty usability scale. *Usability Evaluation in Industry, 189,* 4-7.

Gianaros, P. J., Muth, E. R., Mordkoff, J. T., Levine, M. E., Stern, R. M. (2001). "A Questionnaire for the Assessment of the Multiple Dimensions of Motion Sickness". Aviation, Space, and Environmental Medicine, 72(2): 115–119.

Gilbert, D. G., Dibb, W. D., Plath, L. C., & Hiyane, S. G. (2000). Effects of nicotine and caffeine, separately and in combination, on EEG topography, mood, heart rate, cortisol, and vigilance. *Psychophysiology, 37,* 583-595.

Hockey, G. R. J. (1997). Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework. *Biological Psychology, 45*, 73-93.

Hockey, G. R. J. (2011). A motivational control theory of cognitive fatigue. In P. L. Ackerman (Ed.), Cognitive fatigue: multidisciplinary perspectives on current research and future applications (pp. 167-188). Washington, DC: American Psychological Association.

Hoddes, E., Dement, W., & Zarcone, V. (1972). The development and use of the Stanford Sleepiness Scale (SSS). *Pyschopysiology, 9* (150).

Johnson, R.R., Popovic, D.P., Olmstead, R.E., Stikic, M., Levendowski, D.J., & Berka, C. (2011). Drowsiness/alertness algorithm development and validation using synchronized EEG and cognitive performance to individualize a generalized model. *Biological Psychology, 87*(2), 241-250.

Kähkönen, S., Wilenius, J., Nikulin, V. V., Ollikainen, M., & Ilmoniemi, R. J. (2003). Alcohol reduces prefrontal cortical excitability in humans: A combined TMS and EEG study. *Neuropharmacology, 28*, 747-754.

Roscoe, A. H.; Ellis, G. A. (1990). "A Subjective Rating Scale for Assessing Pilot Workload in Flight: A Decade of Practical Use", Royal Aerospace Establishment, Bedford, UK.

Appendix A. ICE Cueing set descriptions (SET A)

En-route Aircraft Referenced Symbols

The white line across the center of the screen serves as the earth-referenced horizon line. The wings above the horizon line is the aircraft reference symbol. The blue-on-top and brown-on-bottom scale in the center of the screen is an uncompressed pitch scale/ladder. All three symbols are utilized to determine aircraft attitude. The white box with GS next to it on the left side of the screen is current aircraft ground speed (displaying 100 in Figure A1). Above the white box with GS next to it on the left side of the screen is current aircraft airspeed (not displayed in Figure A1). The white dashed arc on the top of the screen provides current aircraft bank angle (white arrow below the center of the arc in Figure A1) and current aircraft heading (white and green arrow above the arc in Figure A1). The white box at the top center of the screen above the heading arc indicates the current aircraft heading (displaying 041 in Figure A1). Route information is provided at the top right of the screen. This information includes the next navigation point, distance to the next navigation point, and the current phase of flight. The numbers with B behind them on the right side of the screen above the white box indicate barometric altitude (displaying 2033 B in Figure A1). The white box with R next to it on the right side of the screen, below barometric altitude, indicates radar altitude (displaying 203 R in Figure A1). HAL in the bottom right corner indicates height above landing (not displayed in Figure A1). The circle with two lines at the bottom of the page serves as the trim ball. Figure A1 depicts aircraft referenced symbols in cruise flight.

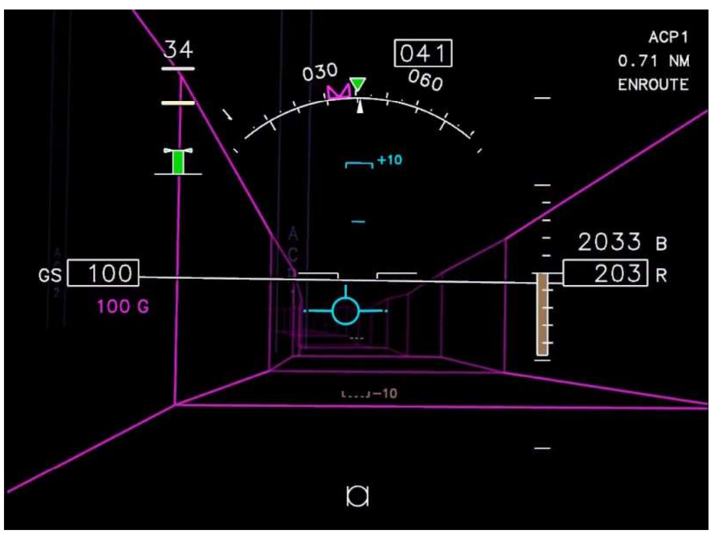


Figure A1. En-route Aircraft Referenced Symbols.

Hover/Approach/Takeoff (HAT) Aircraft Referenced Symbols

The white line across the center of the screen serves as the horizon line. The number associated with the line indicates the aircraft degree of pitch (displaying +5 in Figure A2). Both symbols are utilized to determine aircraft attitude. The diamond above the center crosshairs with the yellow tape attached to it is the heading error tape. The white box with GS next to it on the left side of the screen is current aircraft ground speed (displaying 0 in Figure A2). Above the white box with GS next to it on the left side of the screen is current aircraft airspeed (not displayed in Figure A2). The white dashed arc on the top of the screen provides current aircraft bank angle (white arrow below the center of the arc in Figure A2) and current aircraft heading (above the arc). The white box at the top center of the screen above the heading arc indicates the current aircraft heading (displaying 089 in Figure A2). Route information is provided at the top right of the screen. This information includes the next navigation point, distance to the next navigation point, and the current phase of flight. The numbers with B behind them on the right side of the screen above the white box indicate barometric altitude (displaying 2614 B in Figure A2). The white box with R next to it on the right side of the screen, below barometric altitude, indicates radar altitude (displaying 36 R in Figure A2). HAL in the bottom right corner indicates height above landing (displaying 36 HAL in Figure A2). The circle with two lines at the bottom of the page serves as the trim ball. Figure A2 depicts aircraft referenced symbols at a hover.

Figure A2. HAT Aircraft Referenced Symbols.

Vertical Speed Tape

The vertical speed tape is located on the right side of the screen beside the altitudes during cruise flight and on the left of the crosshair during hover, approach, or takeoff. On the HAT page, the carrots on either side of the bottom of the speed tape indicate collective position indication. The magenta oval indicates the target vertical speed. White tick marks on the vertical speed tape indicate 100 ft/min. The vertical speed tape displays blue when ascending and brown when descending at a safe rate. When descent speed is greater than 360 ft/min and the aircraft is within 5 seconds of impact, the vertical speed tape changes to yellow, an audio cue alerts the pilot with “vertical speed excessive”, and a tactile cue vibrates in the seat. When descent speed is greater than 540 ft/min and the aircraft is within 5 seconds of impact, the vertical speed tape changes to red, an audio cue alerts the pilot with: “pull up, pull up”, and a tactile cue vibrates in the seat. Figure A3 depicts the vertical speed tape and its warnings.

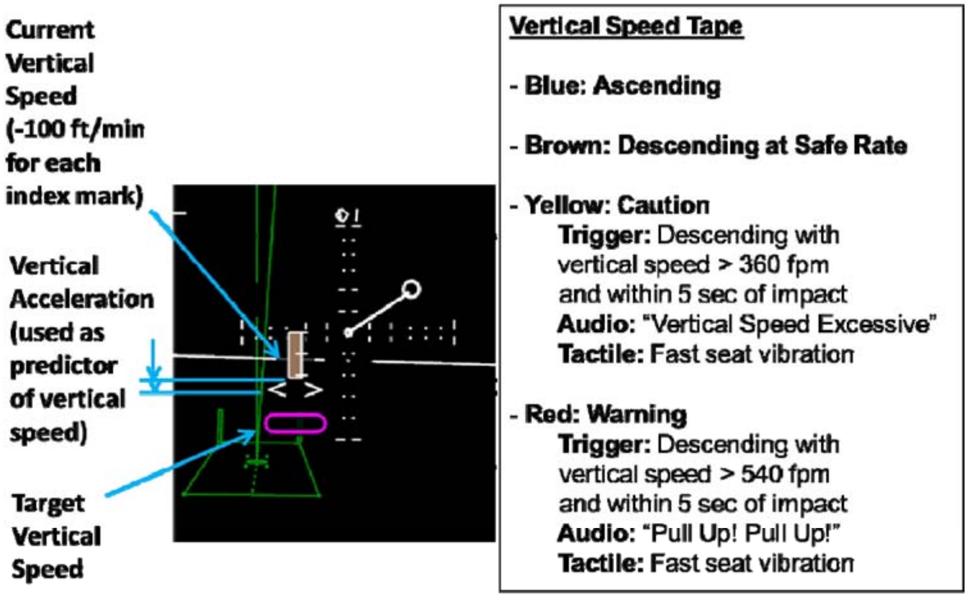


Figure A3. Vertical Speed Tape.

Horizontal Velocity Vector

The velocity vector provides horizontal acceleration cueing. The ticks on the center crosshairs represent a numerical value for velocity speed. Figure A4 depicts the horizontal velocity vector.

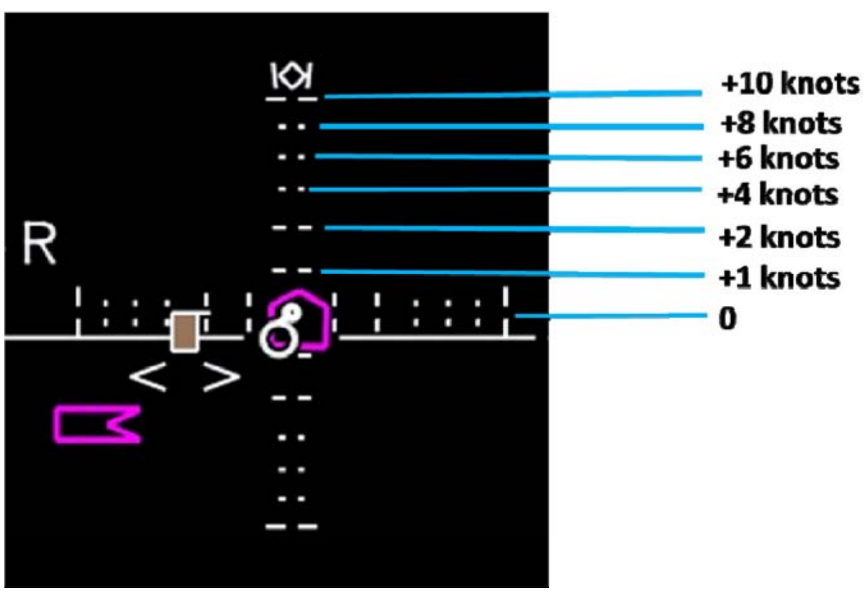


Figure A4. Horizontal Velocity Vector.

Torque Indicator

The torque indicator, located at the top left of the screen, provides combined engine torque. The torque indicator is shown in green when combined torque is below 100%. When combined torque rises above 100%, the torque indicator turns yellow and an audio cue alerts the pilot with "torque." If combined engine torque rises above 120%, the torque indicator changes to red and an audio cue alerts the pilot with "over torque." Figure A5 below depicts the torque indicator.

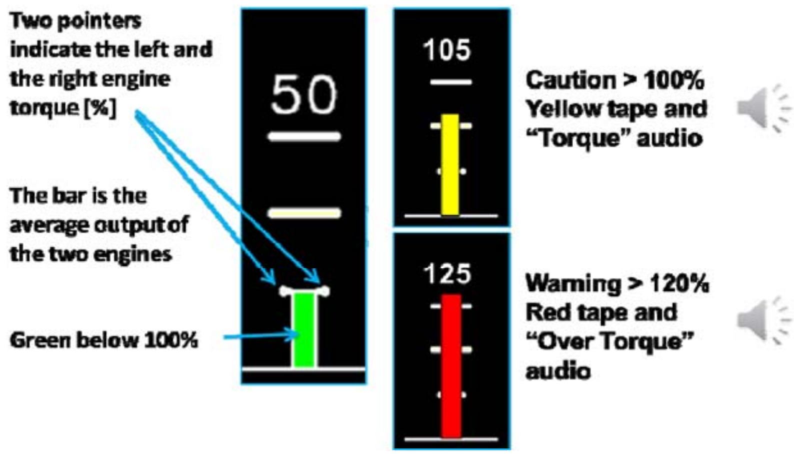


Figure A5. Torque Indicator.

Earth Referenced Symbols

The 3D artificial landing pad provides aircraft drift indications during approach and hover. Figure A6 depicts the 3D artificial landing pad during approach.

Figure A6. Artificial Landing Pad.

Artificial Landing Pad Dimensions

The 3D artificial landing pad consists of a green rectangular area depicted on the ground that is 800 feet in length and 200 feet in width. The crosses on the landing pad are spaced 25 feet apart and provide distance indications. At the center of the landing pad is a green 50 foot circle indicating where the center of the aircraft should be after landing. There are four center boxes on the left and right, forward and aft of the center circle. At the back of the landing pad, there are two 100 foot towers on the left and right. Figure A7 depicts the artificial landing pad.

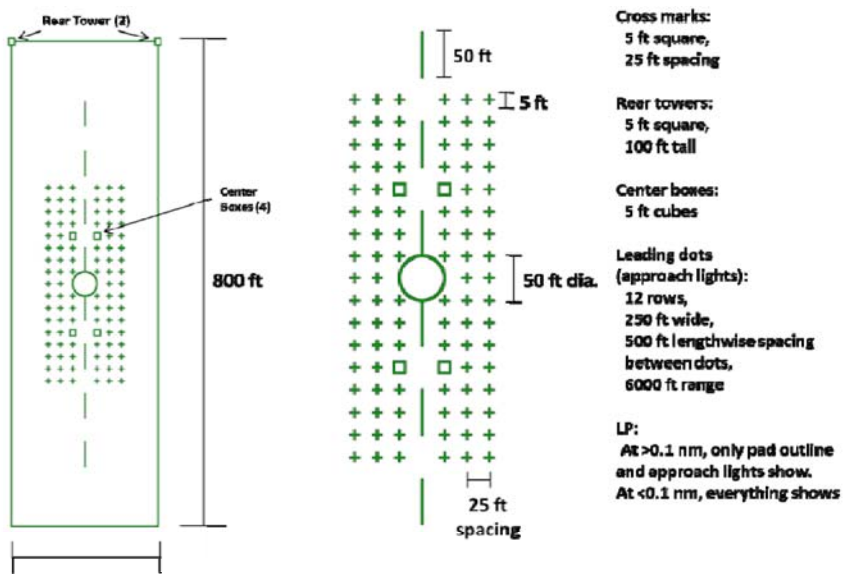


Figure A7. Artificial Landing Pad.

Flight Path Marker

The cyan flight path marker in the middle of the screen provides visual representation of the aircraft actual vertical direction of travel and two seconds of prediction of the aircraft horizontal direction of travel with respect to the terrain imagery. The flight path marker also displays deviation from commanded ground speed. Downward facing wings indicate that the aircraft is too slow and upward facing wings indicate that the aircraft is too fast. Level wings indicate that the aircraft is at the correct speed. The flight path marker symbol turns dashed at approximately 20 knots and disappears once speed guidance is captured or at 10 knots. Figure A8 depicts the flight path marker.

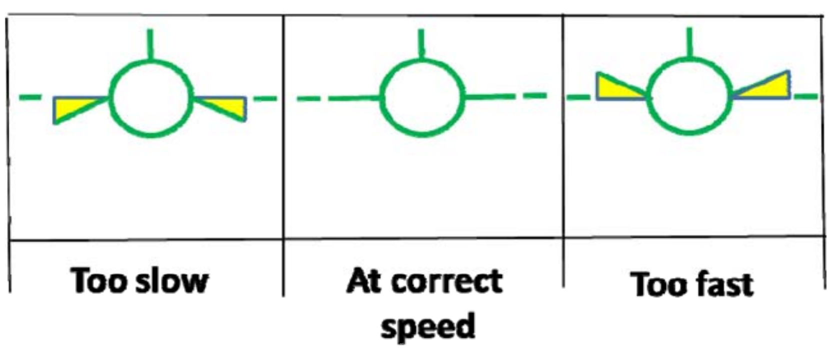


Figure A8. Flight Path Marker.

Flight Path Marker with HTAWS Caution/Warning

During the en-route phase, the flight path marker changes colors to indicate to the pilot an altitude that is too low. In normal conditions at appropriate altitude, the flight path marker remains cyan. When the aircraft is less than 15 seconds to impact, the flight path marker changes to yellow. When the aircraft is less than 10 seconds to impact, the flight path marker turns red. When the aircraft is less than six seconds to impact, the flight path marker remains red, the screen displays a large red arrow with the word “terrain” below it, an audio cue alerts the pilot with “pull up, pull up”, and a tactile cue vibrates in the seat. Figure A9 below depicts the flight path marker with HTAWS caution/warning.

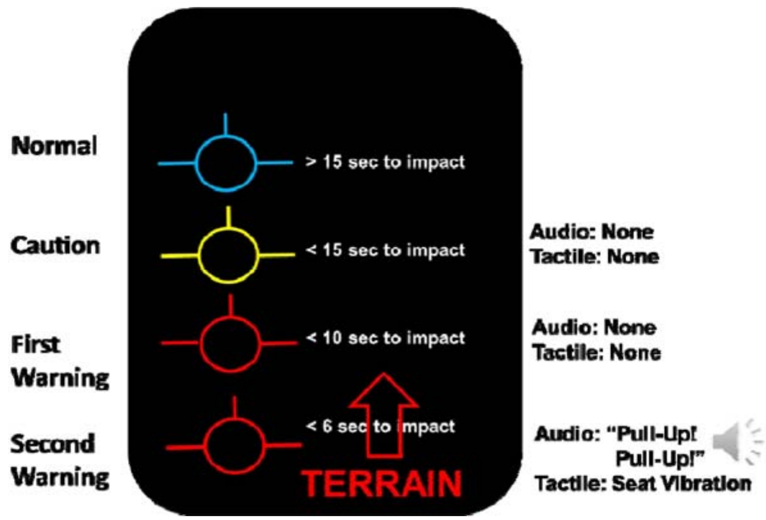


Figure A9. Flight Path Marker with HTAWS Caution/Warning.

Guidance Symbols, Audio, Tactile

Takeoff.

Symbology Set A provides no specific guidance during takeoff. The pilot must conduct an altitude over airspeed takeoff utilizing the velocity vector and vertical speed tape for cyclic and collective position, as well as the heading error tape for pedal position. The velocity vector is used to determine forward airspeed until changing to the en-route guidance page. Tactile cueing alerts the pilot of lateral drift exceeding 10 knots. Figure A10 displays the takeoff symbols.

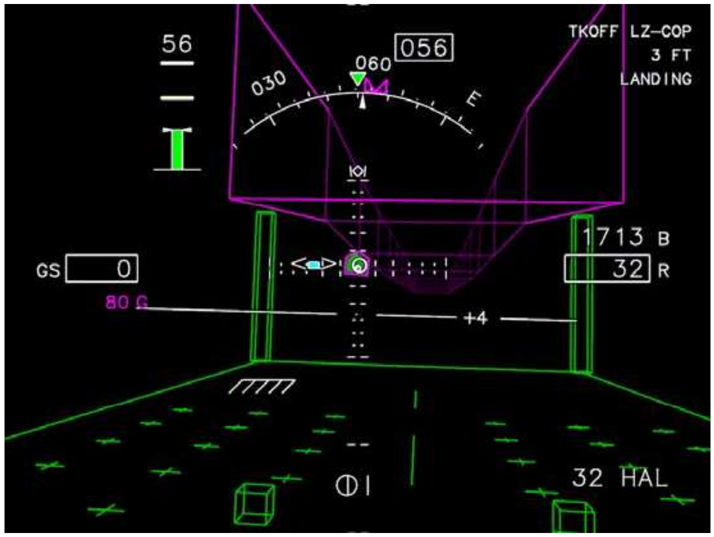


Figure A10. Takeoff Symbols.

En-route.

The earth-referenced magenta pathway in the sky serves as the navigation cue and altitude guidance. The magenta crown (commonly called a heading bug) serves as a course pointer and points directly to the next turn point independent of the pathway guidance. The magenta commanded ground speed is indicated below the current ground speed box on the left side of the screen (displaying 100 G in Figure A11). Tactile cueing alerts the pilot of lateral drift outside the pathway and vertical descent/ascent below and above the pathway. Tactile cueing also alerts the pilot of speed error deviation of faster and lower than 15 knots. Figure A11 depicts the en-route guidance symbols.

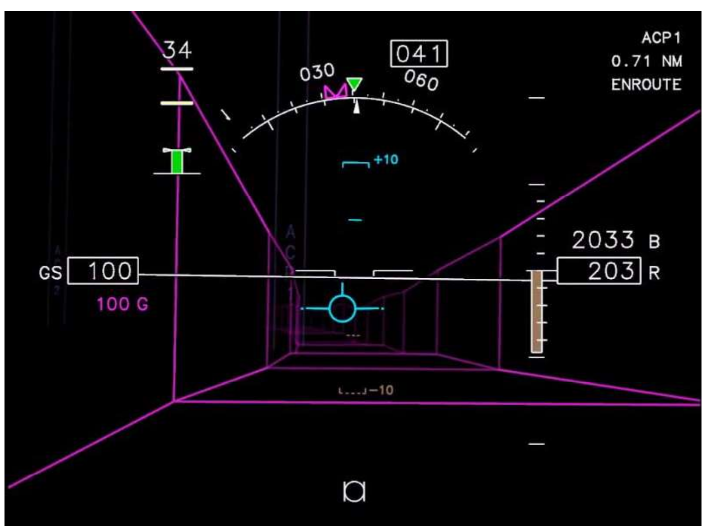


Figure A11. En-route Symbols.

Approach.

The magenta half circle target horizontal speed indication in the top middle of the screen serves as the navigation cue and speed guidance to the landing point. The magenta oval target vertical speed cue on the left of the center crosshairs serves as the altitude guidance. Yellow guidance deviation tapes attach the velocity vector and collective position indicator to their respective guidance cues. The magenta crown serves as a course pointer and points directly to the intended point of landing or hover and is aligned with the white and green arrow above the arc for heading. The heading error tape also provides guidance for deviation from heading. The small white diamond up and to the left of the center crosshairs is the glideslope cue. The approach begins 1 NM from the intended point of landing or hover when the aircraft passes between blue approach gates that appear as two goal posts on either side of the pathway in the sky. An audio cue alerts the pilot with "1 mile to landing point." At 0.8 NM, an audio cue alerts the pilot with "speed guidance on." The flight path marker disappears and the target horizontal speed cue appears from the top of the screen and provides the pilot with speed guidance for a decelerative attitude. Shortly following the "speed guidance on" audio cue (depending on speed and altitude), the glide slope chime activates denoting that the glide slope has been intercepted. The small white diamond travels down until it meets the crosshairs, also indicating that the aircraft has intercepted the glide slope. Descent guidance is provided by the target vertical speed cue at this time. During the approach phase of flight, audio cueing alerts the pilot when they are one mile from the landing or hover point, when speed guidance has activated, when the glide slope has been intercepted, and when the aircraft descends below 100 feet, 50 feet, 40 feet, 30 feet, 20 feet, and 10 feet. Tactile cueing alerts the pilot of lateral drift outside the final approach course and vertical descent/ascent below and above the glide slope. Tactile cueing also alerts the pilot of speed error. Figures A12, A13 and A14 depict the approach guidance.

Landing.

The dashed brown home plate depicts the specified landing point. The dashed brown home plate appears from the top of the screen at about the same time as the target horizontal speed cue. The pilot aligns the white velocity vector inside the brown home plate to position the aircraft over the intended point of landing. As the cue moves down from the top of the screen, it provides a reference for rate of closure. Figure A12 depicts the approach and landing guidance.

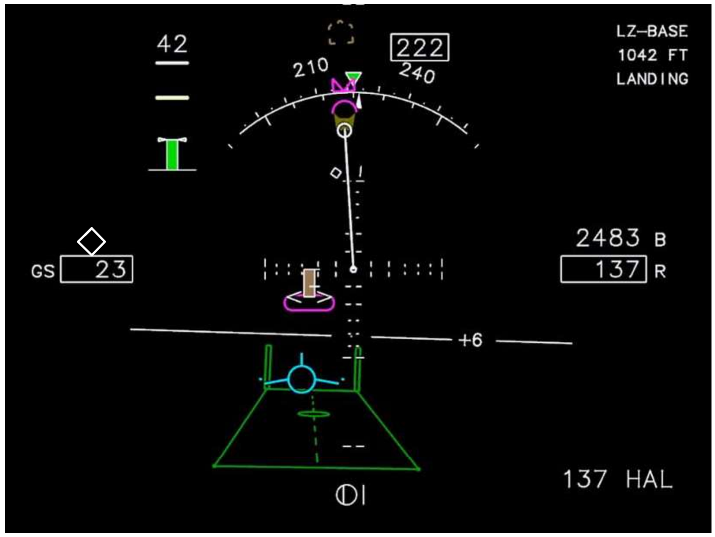


Figure A12. Approach Symbols.

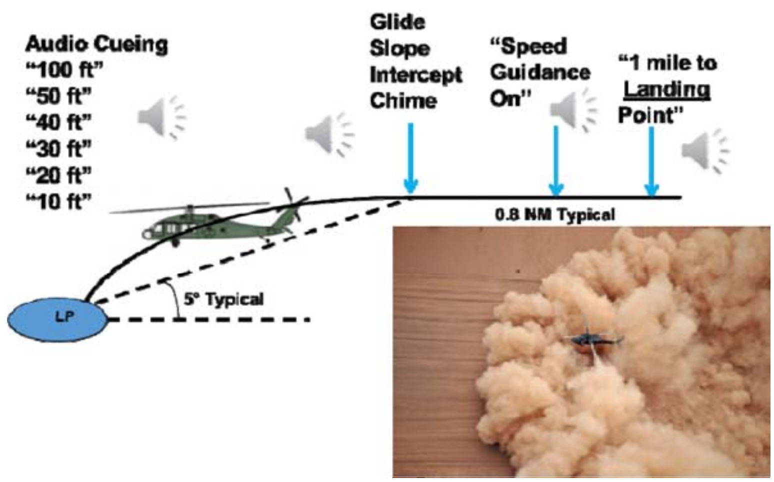


Figure A13. Approach Audio Guidance.

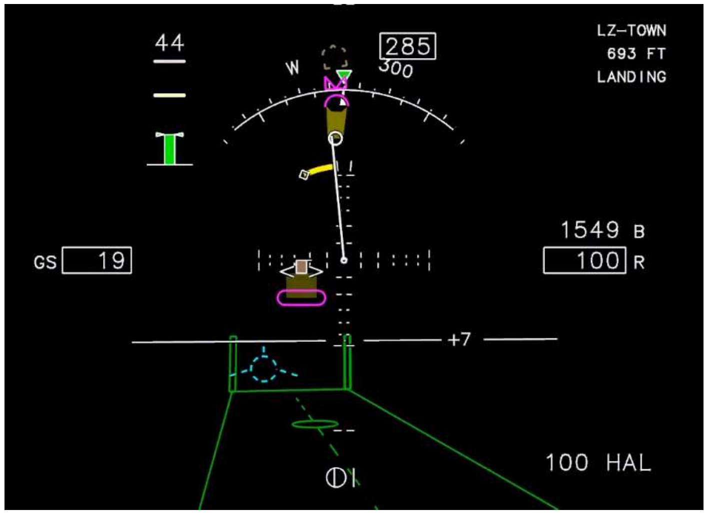


Figure A14. Approach Guidance Deviation.

Hover.

The magenta home plate depicts the specified hover point. The pilot aligns the white velocity vector inside the magenta home plate to position the aircraft over the intended point of hover. The magenta flag to the left of the center crosshairs depicts the target hover altitude. The pilot aligns the collective position indicator carrots attached to the vertical speed tape with the hover altitude flag to hold the target radar altitude for hover. The magenta crown points directly to the intended point of landing or hover and is aligned with the white arrow above the arc for heading. The heading error tape also provides guidance for deviation from heading. Audio cueing alerts the pilot when the aircraft ascends above or descends below 100 feet, 50 feet, 40 feet, 30 feet, 20 feet, and 10 feet. Tactile cueing alerts the pilot of lateral drift greater than 10 feet and vertical descent/ascent greater than five feet. Figure A15 depicts the hover guidance symbols.

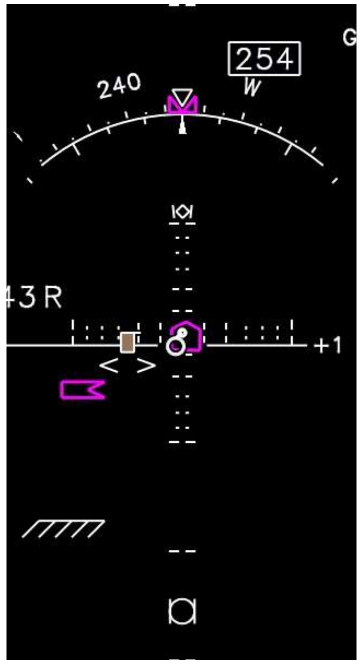


Figure A15. Hover Symbols.

Helmet Mounted Display Earth and Aircraft Referenced Symbols

Most of the Earth and aircraft referenced symbols are identical for both PMD and HMD. The HMD earth-referenced horizon line is green and appears as a line horizontally across the entire screen. The blue-on-top and brown-on-bottom uncompressed pitch scale/ladder and aircraft reference symbol are referenced to the direction of the aircraft. On the HAT page, the velocity vector/center crosshair scale and horizon line are always referenced to the center of the screen. Figures A16 and A17 depict Earth and aircraft referenced symbols using the HMD.

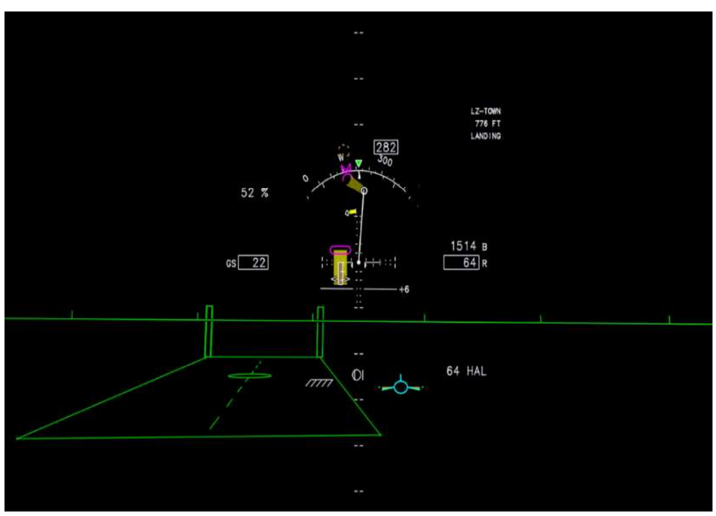


Figure A16. Approach Symbols using HMD.

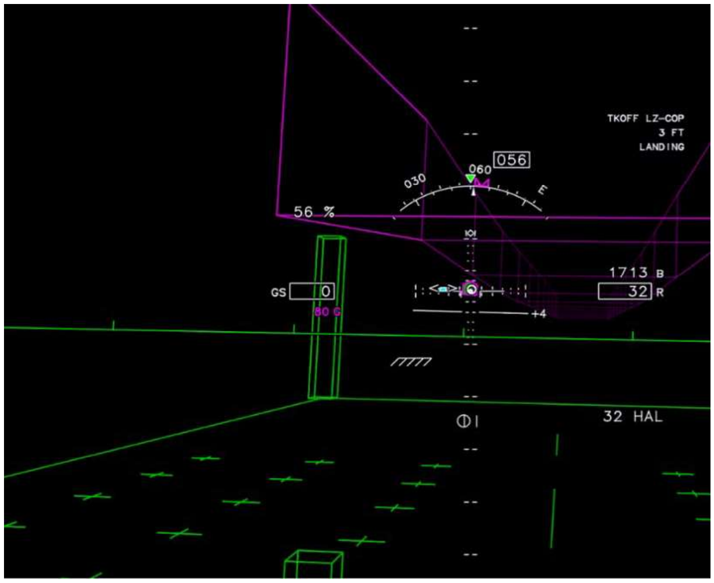


Figure A17. Hover Symbols using HMD.

Appendix B. ICE Cueing set descriptions (SET B)

Aircraft Referenced Symbols

The white line across the center of the screen serves as the earth-referenced horizon line. The wings above the horizon line is the aircraft reference symbol. The blue-on-top and brown-on-bottom scale in the center of the screen is an uncompressed pitch scale/ladder. All three symbols are utilized to determine aircraft attitude. The white box with GS next to it on the left side of the screen is current aircraft ground speed (displaying 117 in Figure B1). Above the white box with GS next to it on the left side of the screen is current aircraft airspeed (not displayed in Figure B1). The white dashed arc on the top of the screen provides current aircraft bank angle (white arrow below the center of the arc in Figure B1). The white box at the top center of the screen above the bank angle arc indicates the current aircraft heading (displaying 059 in Figure B1). Route information is provided at the top right of the screen. This information includes the next navigation point, distance to the next navigation point, and the current phase of flight. The numbers with B behind them on the right side of the screen above the white box indicate barometric altitude (displaying 1924 B in Figure B1). The white box with R next to it on the right side of the screen, below barometric altitude, indicates radar altitude (displaying 303 R in Figure B1). HAL in the bottom right corner indicates height above landing (not displayed in Figure B1). The circle with two lines at the bottom of the page serves as the trim ball. Figure B1 depicts aircraft referenced symbols in cruise flight.

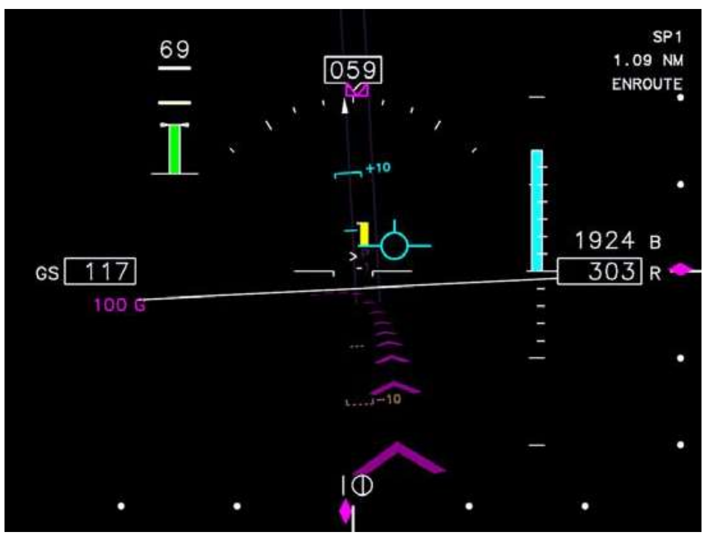


Figure B1. Aircraft Referenced Symbols.

Vertical Speed Tape

The vertical speed tape is located on the right side of the screen beside the altitudes. White tick marks on the vertical speed tape indicate 100 ft/min. The vertical speed tape displays blue when ascending and brown when descending at a safe rate. When descent speed is greater than 360 ft/min and the aircraft is within 5 seconds of impact, the vertical speed tape changes to yellow, an audio cue alerts the pilot with “vertical speed excessive”, and a tactile cue vibrates in the seat. When descent speed is greater than 540 ft/min and the aircraft is within 5 seconds of impact, the vertical speed tape changes to red, an audio cue alerts the pilot with: "pull up, pull up", and a tactile cue vibrates in the seat. Figure B2 depicts the vertical speed tape and its warnings.

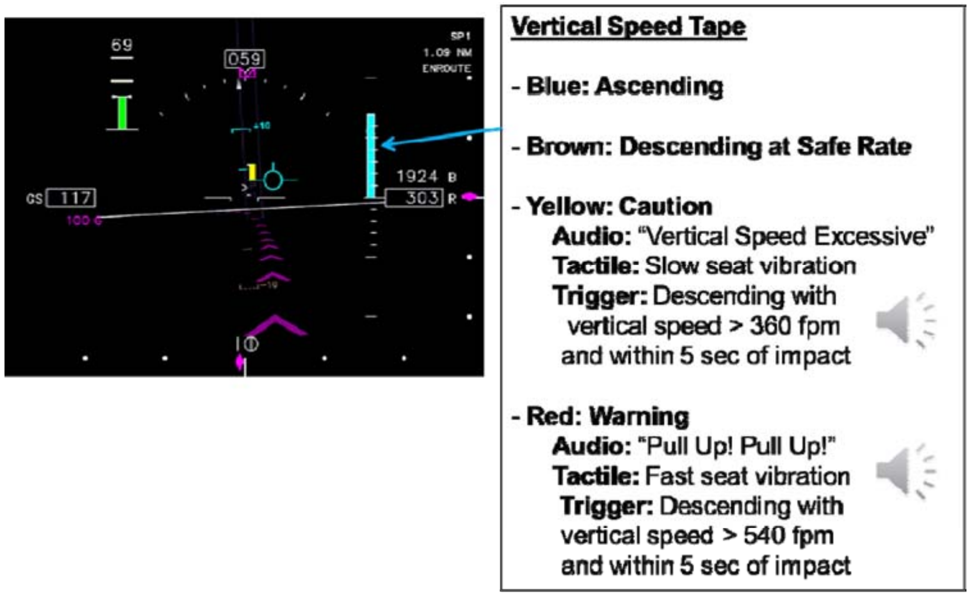


Figure B2. Vertical Speed Tape.

Torque Indicator

The torque indicator, located at the top left of the screen, provides combined engine torque. The torque indicator is shown in green when combined torque is below 100%. When combined torque rises above 100%, the torque indicator turns yellow and an audio cue alerts the pilot with "torque." If combined engine torque rises above 120%, the torque indicator changes to red and an audio cue alerts the pilot with "over torque." Figure B3 below depicts the torque indicator.

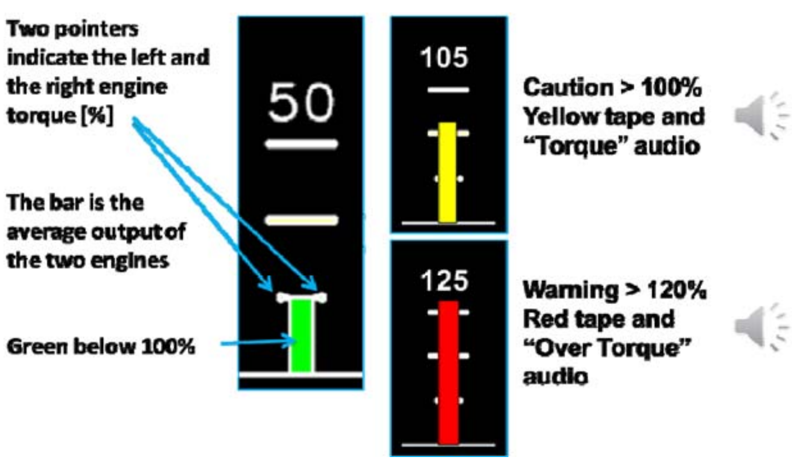


Figure B3. Torque Indicator.

Earth Referenced Symbols

The 3D artificial landing pad with vertical and horizontal grid lines provides aircraft drift indications during approach and hover. Figure B4 depicts the 3D artificial landing pad during approach.

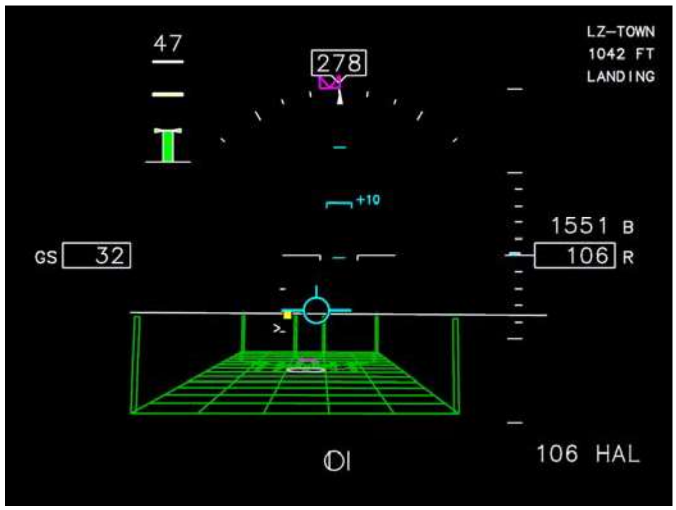


Figure B4. Artificial Landing Pad.

Artificial Landing Pad Dimensions

The 3D artificial landing pad consists of a green rectangular gridded area depicted on the ground that is 260 feet in length and 100 feet in width. The crosses between the grid lines are spaced 25 feet apart and provide distance indications. At the center of the landing pad is a gray 50 foot circle indicating where the center of the aircraft should be after landing. Two diagonal lines lead from the top of the circle to two 25 foot towers on the left and right of the pad. Two additional diagonal lines lead from the top of the circle to two 100 foot towers in the middle and to the back of the pad. The two 100 foot tall towers in the middle and to the back of the 3D artificial landing pad provide altitude indications while landing or at a hover. Gray triangle pointers on the inside of the towers are always in-line with the earth-referenced horizon line and are used to align with the magenta marks on the towers. At the back of the landing pad, there are two additional 100 foot towers on the left and right. At the front of the landing pad, there are two 100 foot towers on the left and right. Figure B5 depicts the artificial landing pad dimensions.

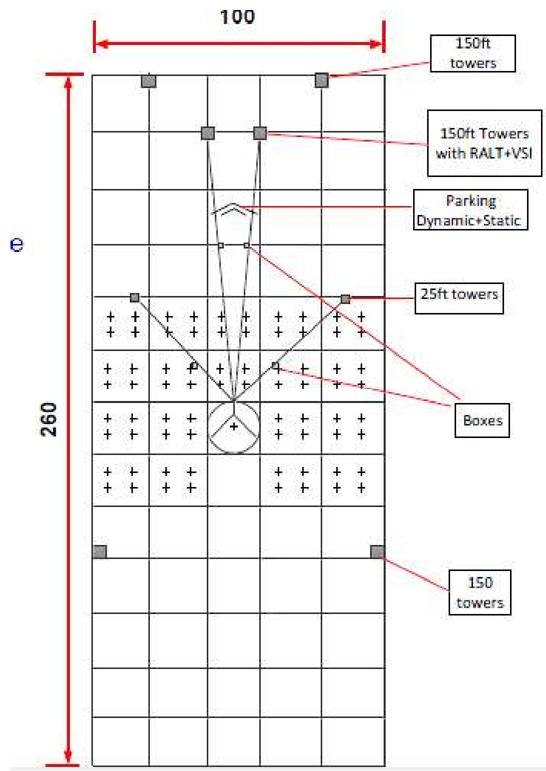


Figure B5. Artificial Landing Pad Dimensions.

Flight Path Marker

The cyan flight path marker in the middle of the screen provides visual representation of the aircraft actual vertical direction of travel and two seconds of prediction of the aircraft horizontal direction of travel with respect to the terrain imagery. The flight path marker also displays deviation from commanded ground speed with the yellow speed error tape on the left wing. The speed error tape will extend either above or below the flight path marker depending on if the aircraft is moving faster or slower than the commanded speed. To the left of the speed error tape is a longitudinal acceleration caret that provides acceleration and deceleration cueing. Each tick indicates one knot of speed. The flight path marker symbol turns dashed at approximately 25 knots and disappears at 20 knots. Figure B6 depicts the flight path marker.

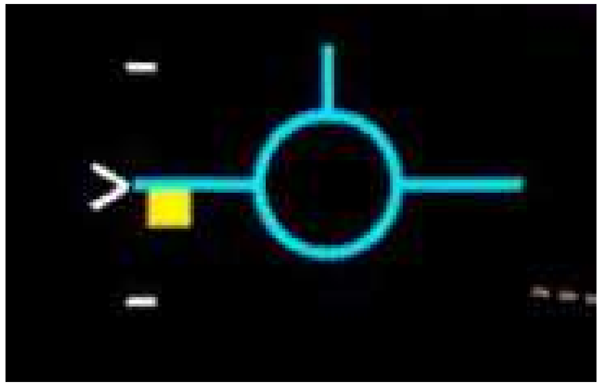


Figure B6. Flight Path Marker.

Flight Path Marker with HTAWS Caution/Warning

During the en-route phase, the flight path marker changes colors to indicate to the pilot an altitude that is too low. In normal conditions at appropriate altitude, the flight path marker remains cyan. When the aircraft is less than 15 seconds to impact, the flight path marker changes to yellow. When the aircraft is less than 10 seconds to impact, the flight path marker turns red. When the aircraft is less than six seconds to impact, the flight path marker remains red, the screen displays a large red arrow with the word “terrain” below it, an audio cue alerts the pilot with “pull up, pull up”, and a tactile cue vibrates in the seat. Figure B7 below depicts the flight path marker with HTAWS caution/warning.

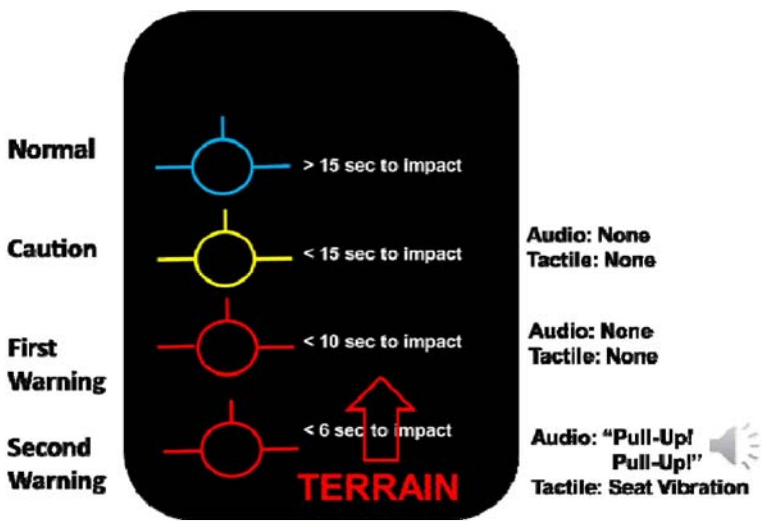


Figure B7. Flight Path Marker with HTAWS Caution/Warning.

Guidance Symbols, Audio, Tactile

Takeoff.

Symbology Set B provides no specific guidance during takeoff. The pilot must conduct an altitude over airspeed takeoff utilizing the earth-referenced horizon line, aircraft reference symbol, pitch scale, and vertical speed tape for cyclic and collective position, as well as the heading indicator for pedal position. Tactile cueing alerts the pilot of lateral drift exceeding 10 knots.

En-route.

The earth-referenced magenta chevron ground course track in the middle of the screen serves as the navigation cue. The magenta crown (commonly called a heading bug) serves as a course pointer and points directly to the next turn point independent of the ground course guidance. The horizontal course deviation indicator along the bottom of the screen provides deviation from the ground course track. The vertical/altitude deviation indicator along the right side of the screen provides deviation from commanded altitude. The magenta commanded ground speed is indicated below the current ground speed box on the left side of the screen (displaying 100 G in Figure B8). Figure B8 depicts the en-route guidance symbols.

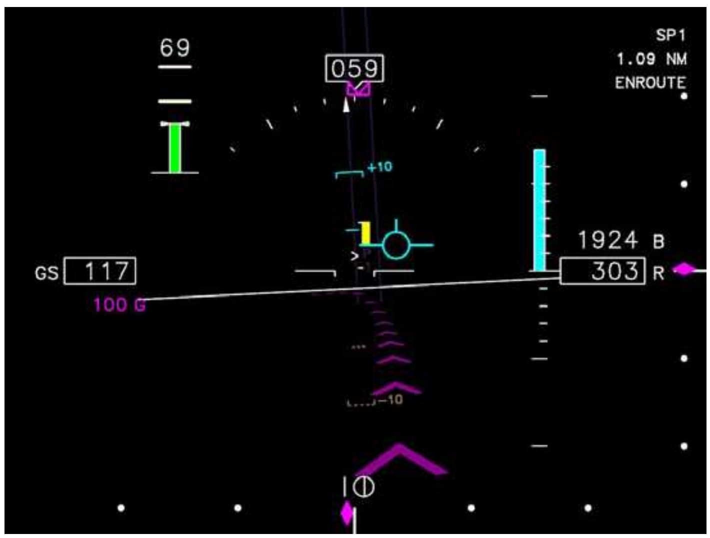


Figure B8. En-route Symbols.

Approach.

The approach begins 1 NM from the intended point of landing or hover when the aircraft passes between blue approach gates that appear as two goal posts on either side of the chevron pathway. An audio cue alerts the pilot with “1 mile to landing point.” At 0.8 NM, an audio cue alerts the pilot with “speed guidance on.” The yellow speed error tape on the left wing of the flight path marker will provide the pilot with speed guidance for a decelerative attitude. The speed tape appears when the pilot has deviated from the speed guidance (yellow appears above the left wing of the flight path marker if the speed is too fast and below if too slow). The glide slope is intercepted at the same time that the audio cue alerts the pilot with “speed guidance on” at 0.8 NM from the landing point. The pilot aligns the flight path marker with the top of the center 100 foot towers on the 3D artificial landing pad. As the vertical and horizontal grid lines of the 3D artificial landing pad come into view, the pilot aligns the flight path marker with the gray circle in the center of the 3D artificial landing pad. At approximately 20 knots, the flight path marker disappears and a white arrow (parking symbol) appears from the bottom of the screen at 100 foot in front of the aircraft. The pilot aligns the white chevron (parking symbol) with the static magenta chevron on the ground. During the approach phase of flight, audio cueing alerts the pilot when they are one mile from the landing or hover point, when speed guidance has activated, and when the aircraft descends below 100 feet, 50 feet, 40 feet, 30 feet, 20 feet, and 10 feet. Figure B9 and Figure B10 depict the approach guidance.

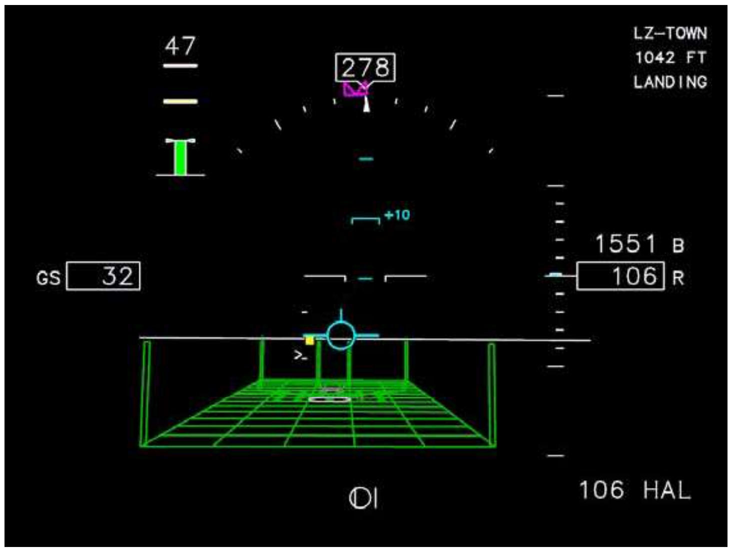


Figure B9. Approach Symbols.

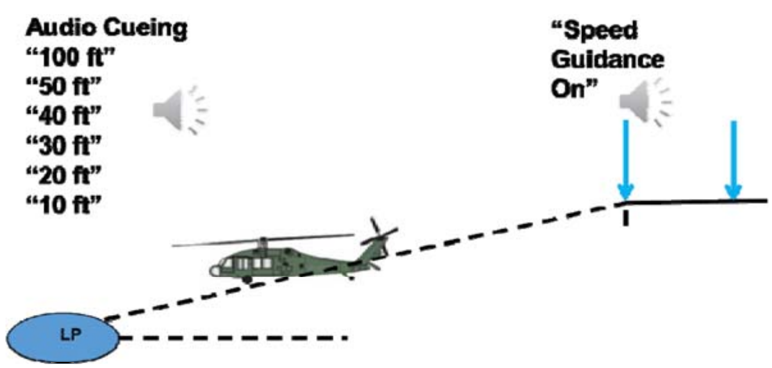


Figure B10. Approach Audio Guidance.

Hover.

The static magenta chevron on the ground depicts the specified landing or hover point. The sliding white arrow (parking symbol) is illustrative of 100 feet in front of the aircraft and indicates the position of the aircraft. During approach, at approximately 20 knots, the flight path marker disappears and the white arrow appears from the bottom of the screen. The pilot aligns the white arrow with the static magenta chevron on the ground to position the aircraft over the intended point of landing or hover. Magenta marks on the two 100 foot tall towers (goal posts) in the middle and to the back of the 3D artificial landing pad designate the target radar altitude for hover. Tactile cueing alerts the pilot of lateral drift greater than 10 feet and vertical descent/ascent greater than five feet. Figure B11 depicts the hover guidance symbols.

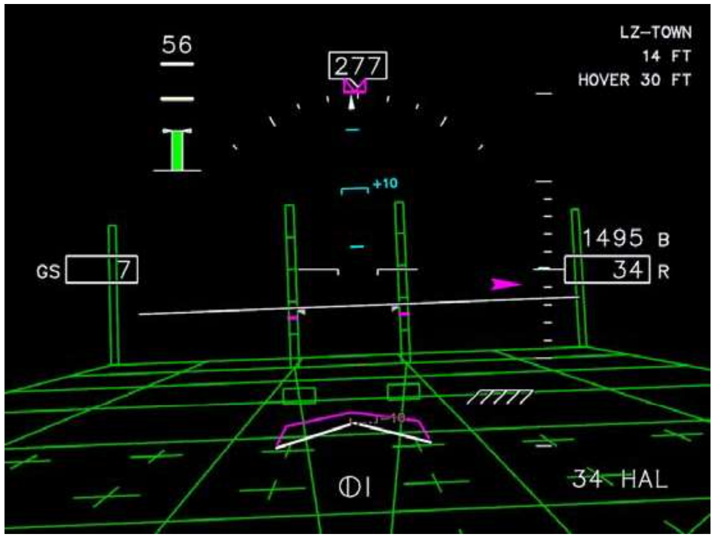


Figure B11. Hover Symbols.

Helmet Mounted Display Earth and Aircraft Referenced Symbols

Most of the Earth and aircraft referenced symbols are identical for both PMD and HMD. The HMD earth-referenced horizon line is green and appears as a line horizontally across the entire screen. The blue-on-top and brown-on-bottom uncompressed pitch scale/ladder and aircraft reference symbol are referenced to the direction of the aircraft. Figures B12 and B13 depict Earth and aircraft referenced symbols using the HMD.

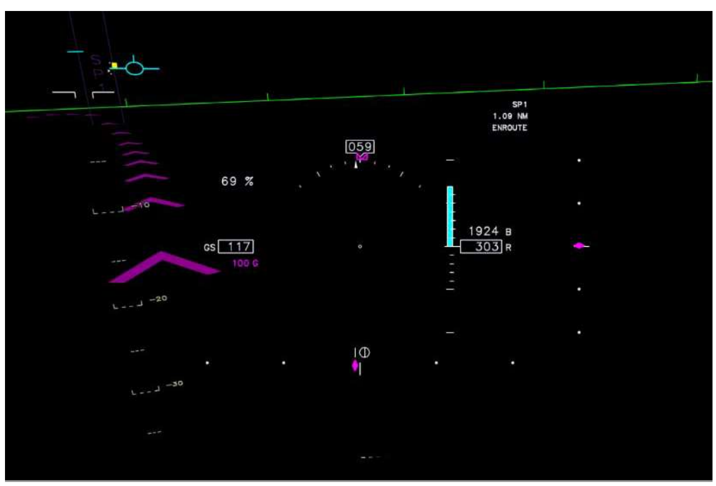


Figure B12. En-route Symbols using HMD.

Figure B13. Approach and Hover Symbols using HMD.

Appendix C. Aural Cues

HTAWS **-** <6 sec to impact TERRAIN warning

Torque

Caution >100% Yellow tape and "Torque" audio

Warning>120% Red tape and "Over Torque" audio

Vertical Speed Tape- tape driven by EGI

Yellow Caution "Vertical Speed Excessive" descending with a vertical speed >360 fpm and within 5 sec of impact

- Red Warning: **"Pull Up! Pull Up!"** Descending with vertical speed > 540 fpm and within 5 sec of impact

Glide slope intercept – ASK about 1 nm to Hover point vs landing on slides 13/14

"1 NM to Hover Point"

"Speed Guidance On" (what is the trigger)

"Start Descent" (confirm GS intercept as trigger)

"One nautical mile to hover point" (if applicable)

"One nautical mile to landing point" (if applicable)

"Speed guidance on"

"Start Descent" Glide slope intercepted, start descent

"Hover Down" Start hover-down descent (if applicable)

"100 ft" Descending below 100 ft, ascending above xx

"50 ft" Descending below 50 ft, ascending above xx

"40 ft" Descending below 40 ft, ascending above xx

"30 ft" Descending below 30 ft, ascending above xx

"20 ft" Descending below 20 ft, ascending above xx

“10 ft.” Descending below 10 ft., ascending above xx

Caution Messages

“Vertical speed excessive” vertical speed > 540 fpm and within 5 seconds of contact.

“Torque” Torque greater than 100%

“Cyclic pitch saturation”

“Cyclic roll saturation”

“Heading saturation”

“Check hover position” Position hold is outside tolerance

“Check altitude” Radar altitude hold is outside tolerance

“MCLAWS degraded”

Warning Messages

“Pull up! Pull up!” vertical speed > ? fpm and within 5 seconds of contact.

“Over torque” Torque greater than >120%

Appendix D. Questionnaires

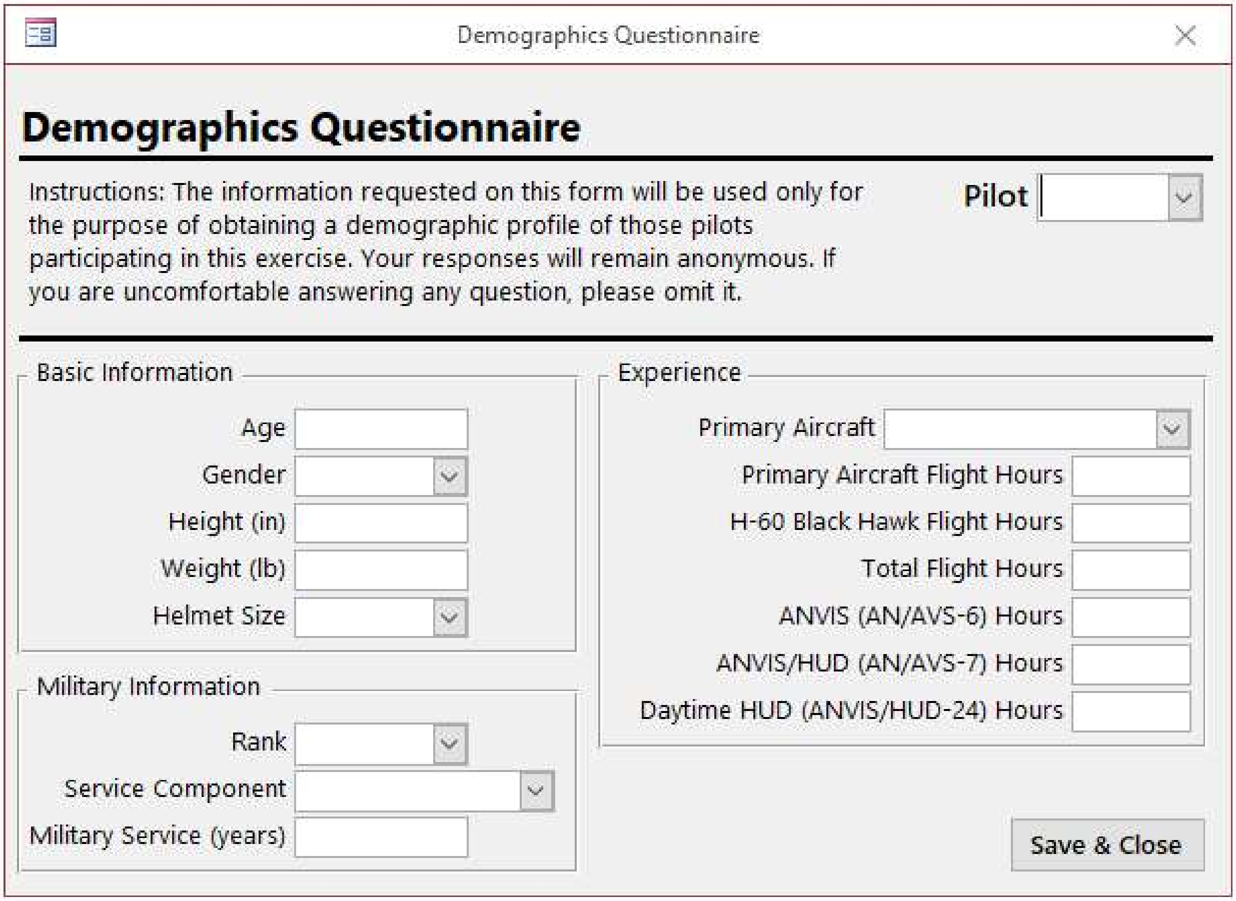
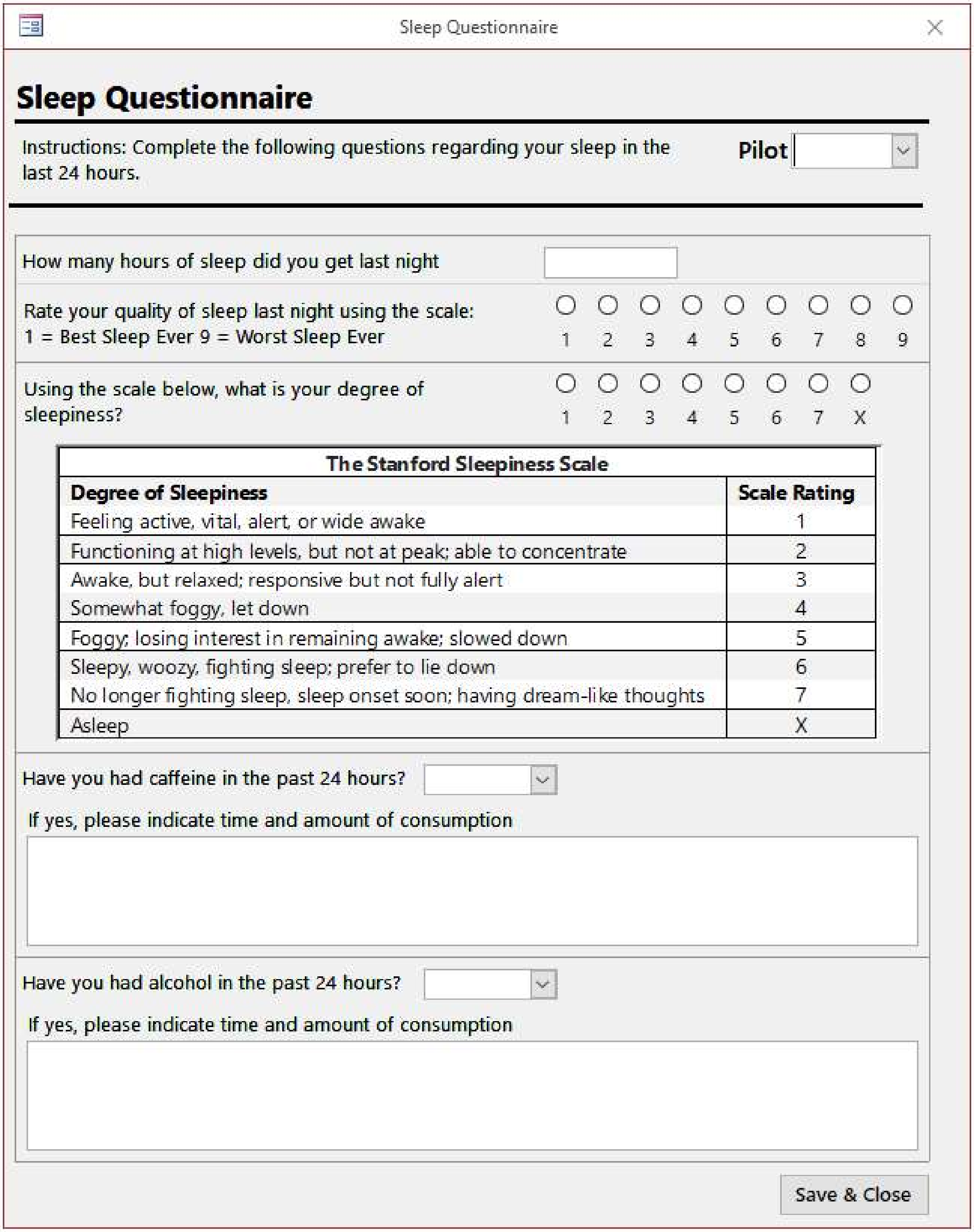


Figure D1. Demographics questionnaire.


Sleep Questionnaire

Sleep Questionnaire

Instructions: Complete the following questions regarding your sleep in the last 24 hours.

Pilot

How many hours of sleep did you get last night

Rate your quality of sleep last night using the scale:
1 = Best Sleep Ever 9 = Worst Sleep Ever

1 2 3 4 5 6 7 8 9

Using the scale below, what is your degree of sleepiness?

1 2 3 4 5 6 7 X

The Stanford Sleepiness Scale	
Degree of Sleepiness	**Scale Rating**
Feeling active, vital, alert, or wide awake	1
Functioning at high levels, but not at peak; able to concentrate	2
Awake, but relaxed; responsive but not fully alert	3
Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	5
Sleepy, woozy, fighting sleep; prefer to lie down	6
No longer fighting sleep, sleep onset soon; having dream-like thoughts	7
Asleep	X

Have you had caffeine in the past 24 hours?

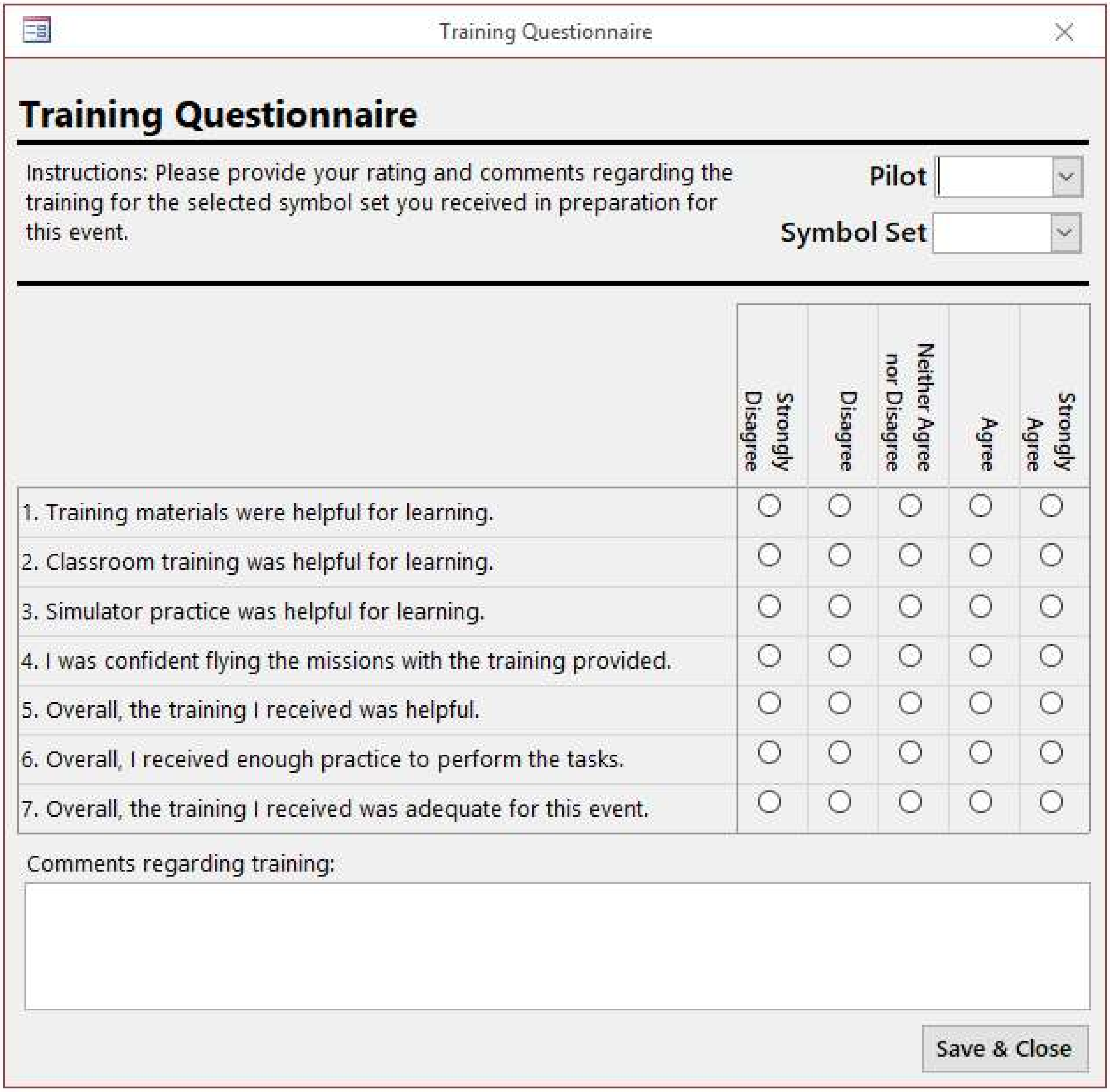
If yes, please indicate time and amount of consumption

Have you had alcohol in the past 24 hours?

If yes, please indicate time and amount of consumption

Save & Close

Figure D2. Sleep questionnaire.



Training Questionnaire

Training Questionnaire

Instructions: Please provide your rating and comments regarding the training for the selected symbol set you received in preparation for this event.

Pilot

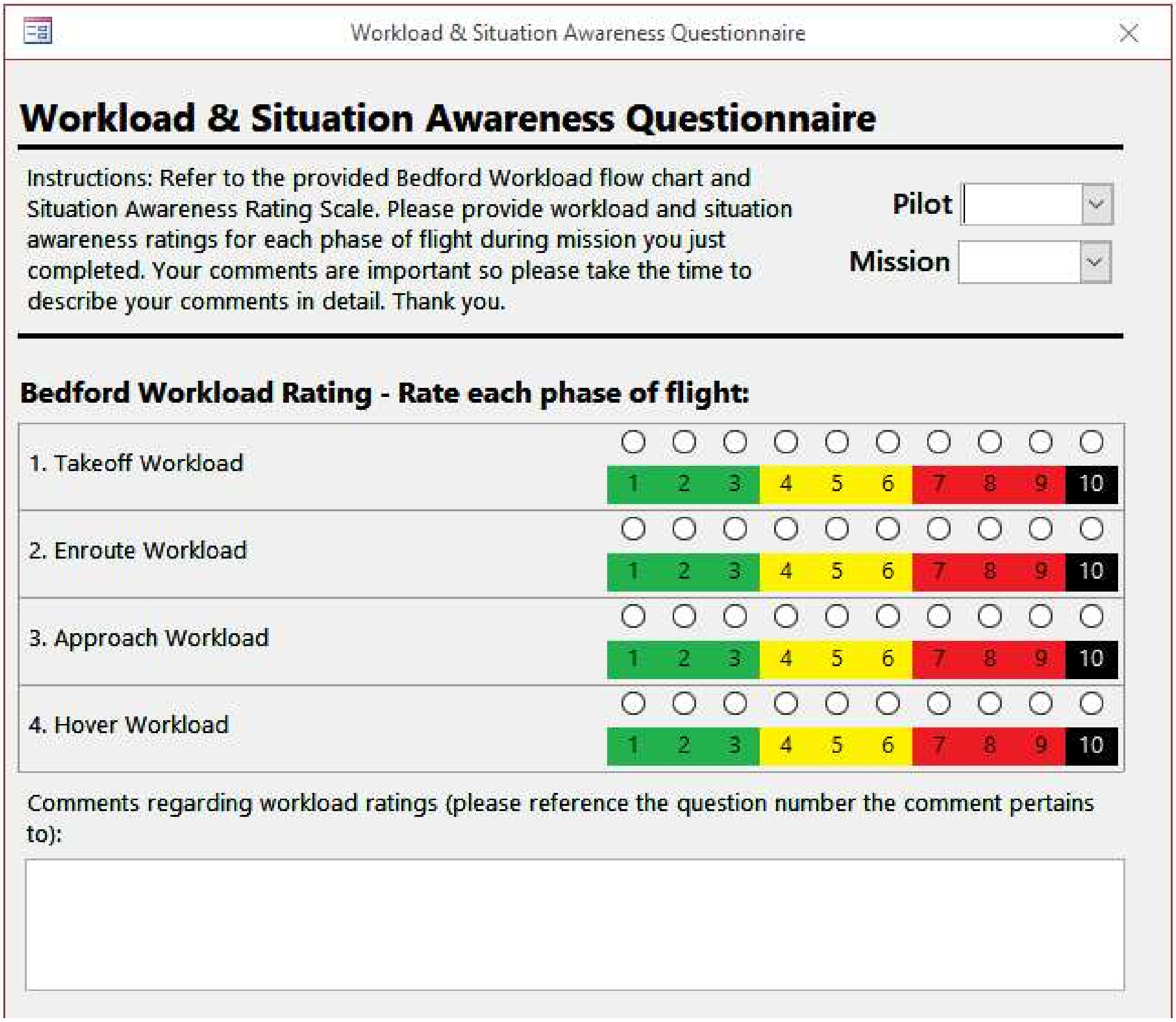
Symbol Set

	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
1. Training materials were helpful for learning.	○	○	○	○	○
2. Classroom training was helpful for learning.	○	○	○	○	○
3. Simulator practice was helpful for learning.	○	○	○	○	○
4. I was confident flying the missions with the training provided.	○	○	○	○	○
5. Overall, the training I received was helpful.	○	○	○	○	○
6. Overall, I received enough practice to perform the tasks.	○	○	○	○	○
7. Overall, the training I received was adequate for this event.	○	○	○	○	○

Comments regarding training:

Save & Close

Figure D3. Training 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):

Figure D4. Workload and Situation Awareness questionnaire.

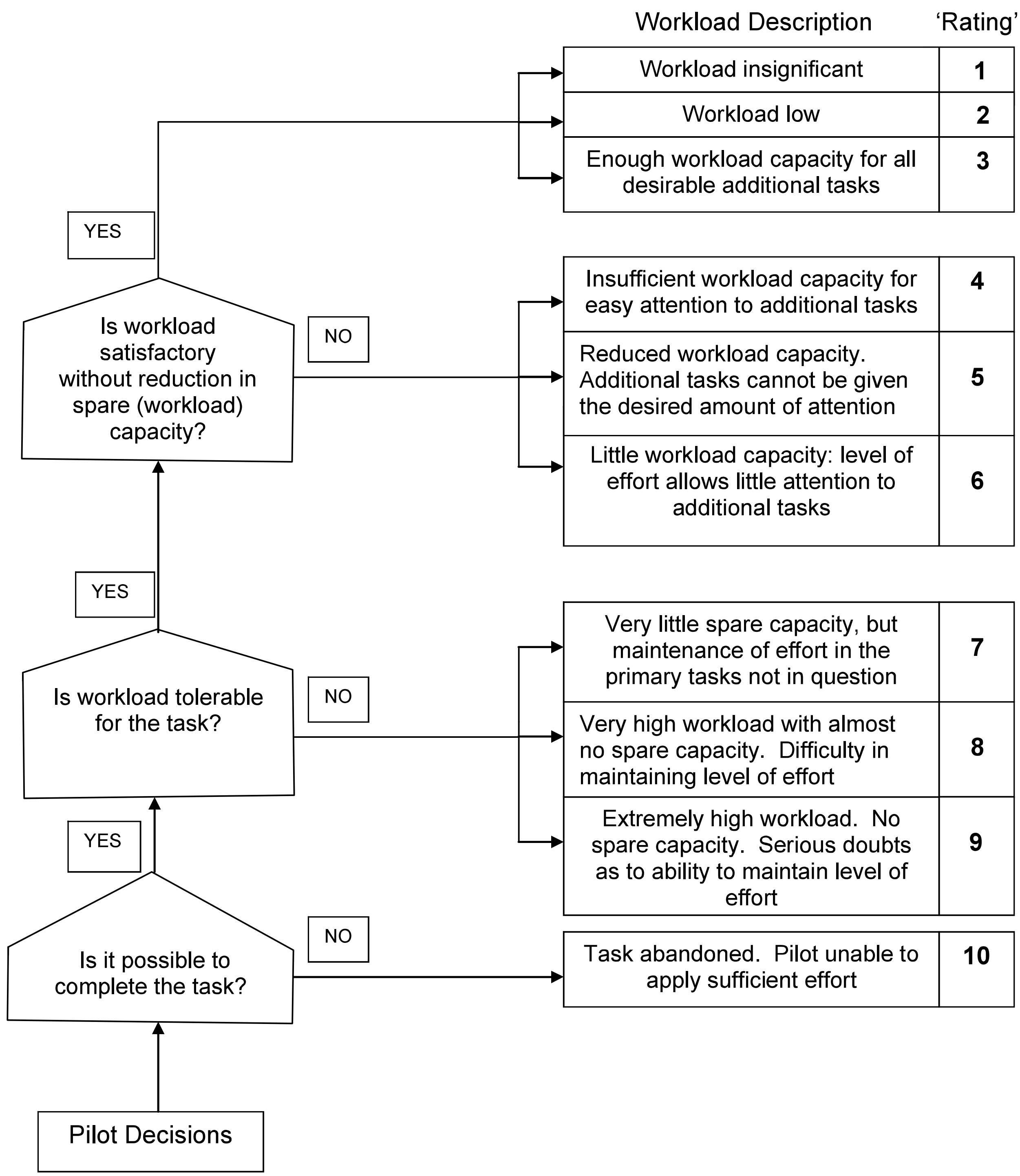
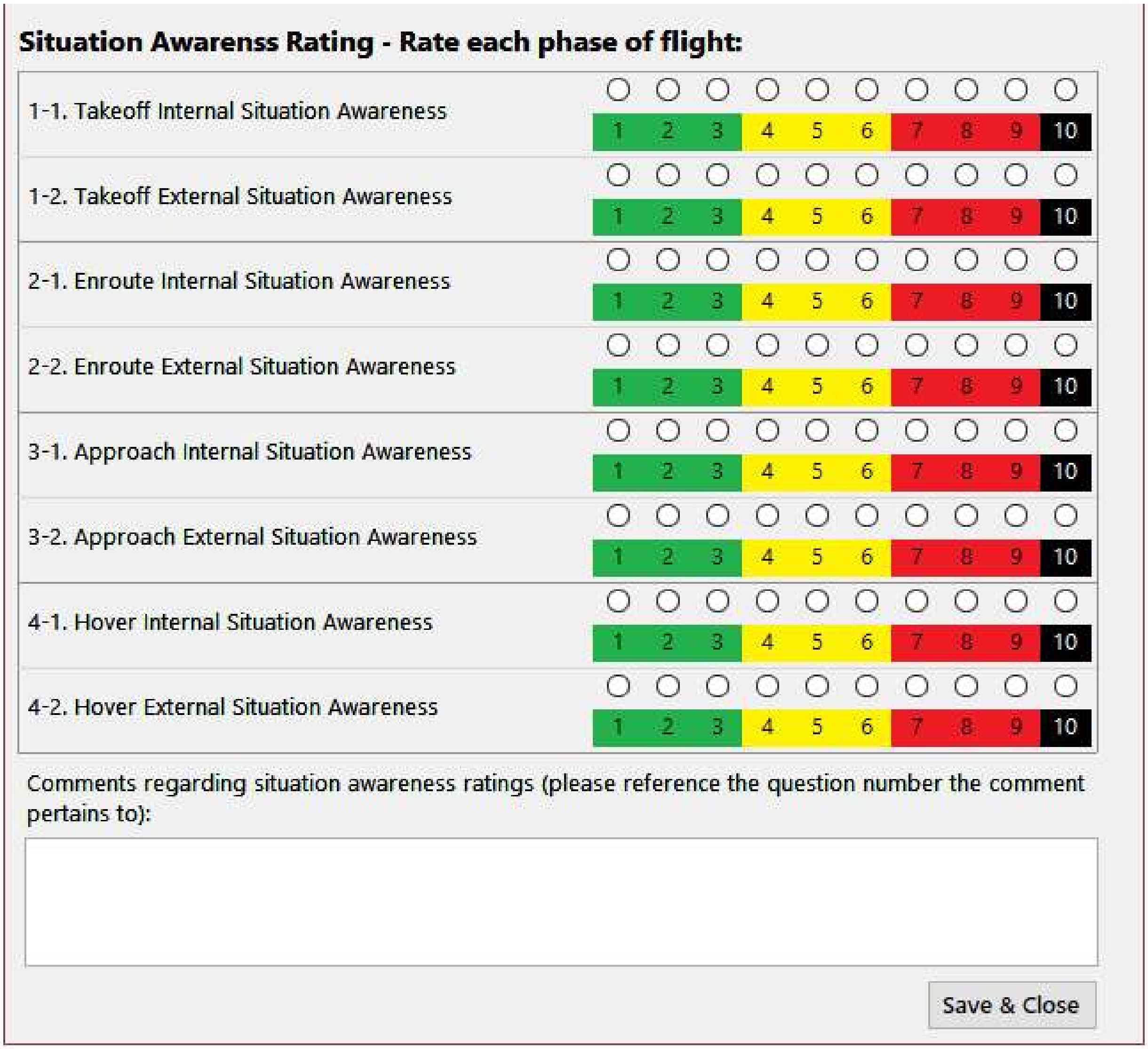


Figure D5. Instructions for completing the Workload and Situation Awareness questionnaire.



Situation Awarenss Rating - Rate each phase of flight:

1-1. Takeoff Internal Situation Awareness	1	2	3	4	5	6	7	8	9	10
1-2. Takeoff External Situation Awareness	1	2	3	4	5	6	7	8	9	10
2-1. Enroute Internal Situation Awareness	1	2	3	4	5	6	7	8	9	10
2-2. Enroute External Situation Awareness	1	2	3	4	5	6	7	8	9	10
3-1. Approach Internal Situation Awareness	1	2	3	4	5	6	7	8	9	10
3-2. Approach External Situation Awareness	1	2	3	4	5	6	7	8	9	10
4-1. Hover Internal Situation Awareness	1	2	3	4	5	6	7	8	9	10
4-2. Hover External Situation Awareness	1	2	3	4	5	6	7	8	9	10

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

Save & Close

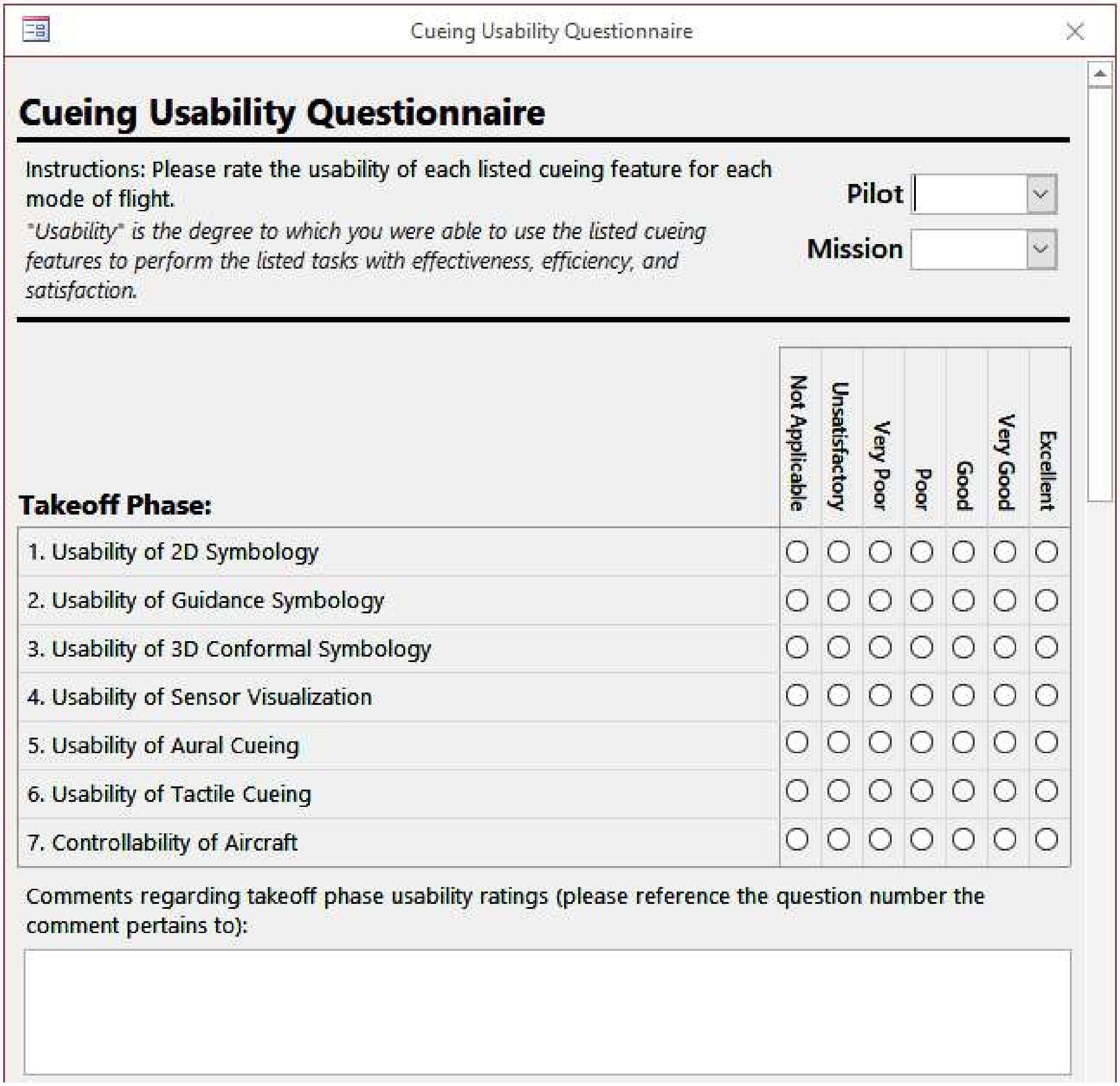
Figure D6. Situation Awareness Rating questionnaire.

Situation Awareness Rating Scale

1	2	3	4	5	6	7	8	9	10
High			**Moderate**			**Low**			**None**

Internal SA – Aircraft State / Performance	**External SA – Visual Scene / Sensor Image**
Altitude / Vertical Speed	Terrain Slope
Air Speed / Ground Speed	Terrain Roughness
LZ / Hover Position	Features in the Landing Zone
Drift	Obstacles
Power Margin	Vehicles
Attitude	Personnel
Heading	Threats

Figure D7. Instructions for completing the Situation Awareness Rating questionnaire.



Cueing Usability Questionnaire

Cueing Usability Questionnaire

Instructions: Please rate the usability of each listed cueing feature for each mode of flight.

"Usability" is the degree to which you were able to use the listed cueing features to perform the listed tasks with effectiveness, efficiency, and satisfaction.

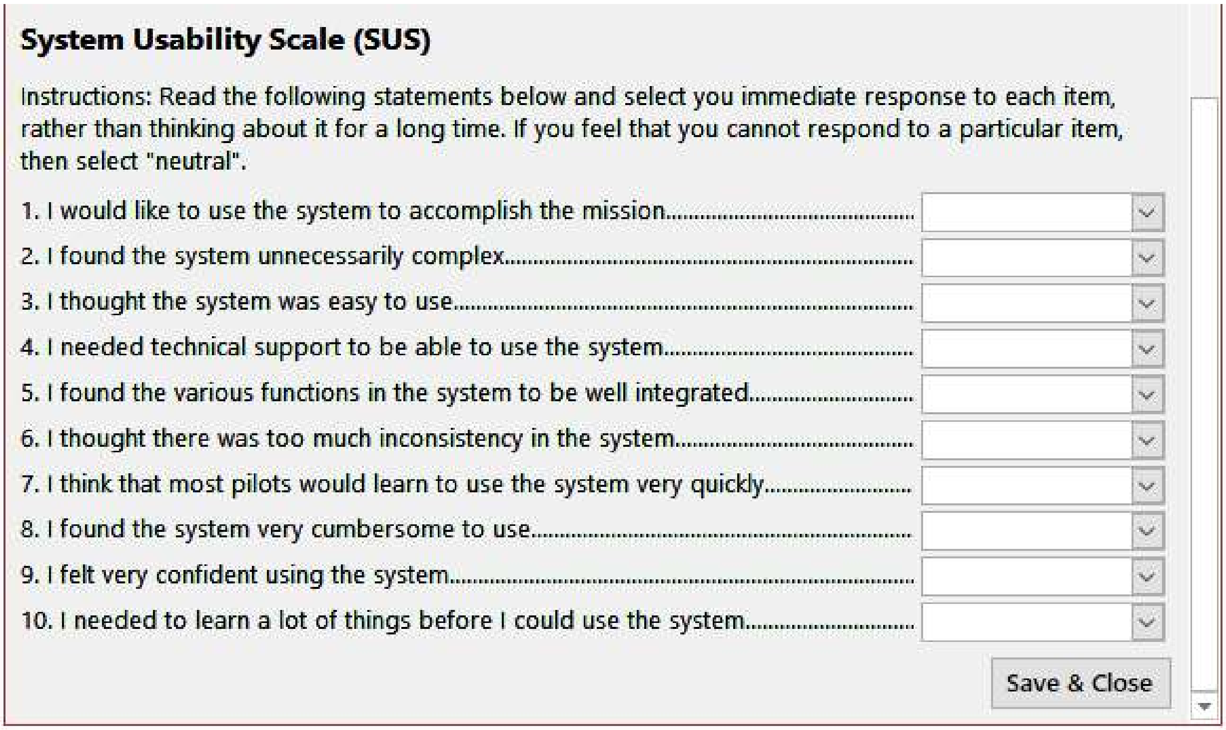
Pilot

Mission

Takeoff Phase:	Not Applicable	Unsatisfactory	Very Poor	Poor	Good	Very Good	Excellent
1. Usability of 2D Symbology	○	○	○	○	○	○	○
2. Usability of Guidance Symbology	○	○	○	○	○	○	○
3. Usability of 3D Conformal Symbology	○	○	○	○	○	○	○
4. Usability of Sensor Visualization	○	○	○	○	○	○	○
5. Usability of Aural Cueing	○	○	○	○	○	○	○
6. Usability of Tactile Cueing	○	○	○	○	○	○	○
7. Controllability of Aircraft	○	○	○	○	○	○	○

Comments regarding takeoff phase usability ratings (please reference the question number the comment pertains to):

Figure D8. Cueing Usability questionnaire.



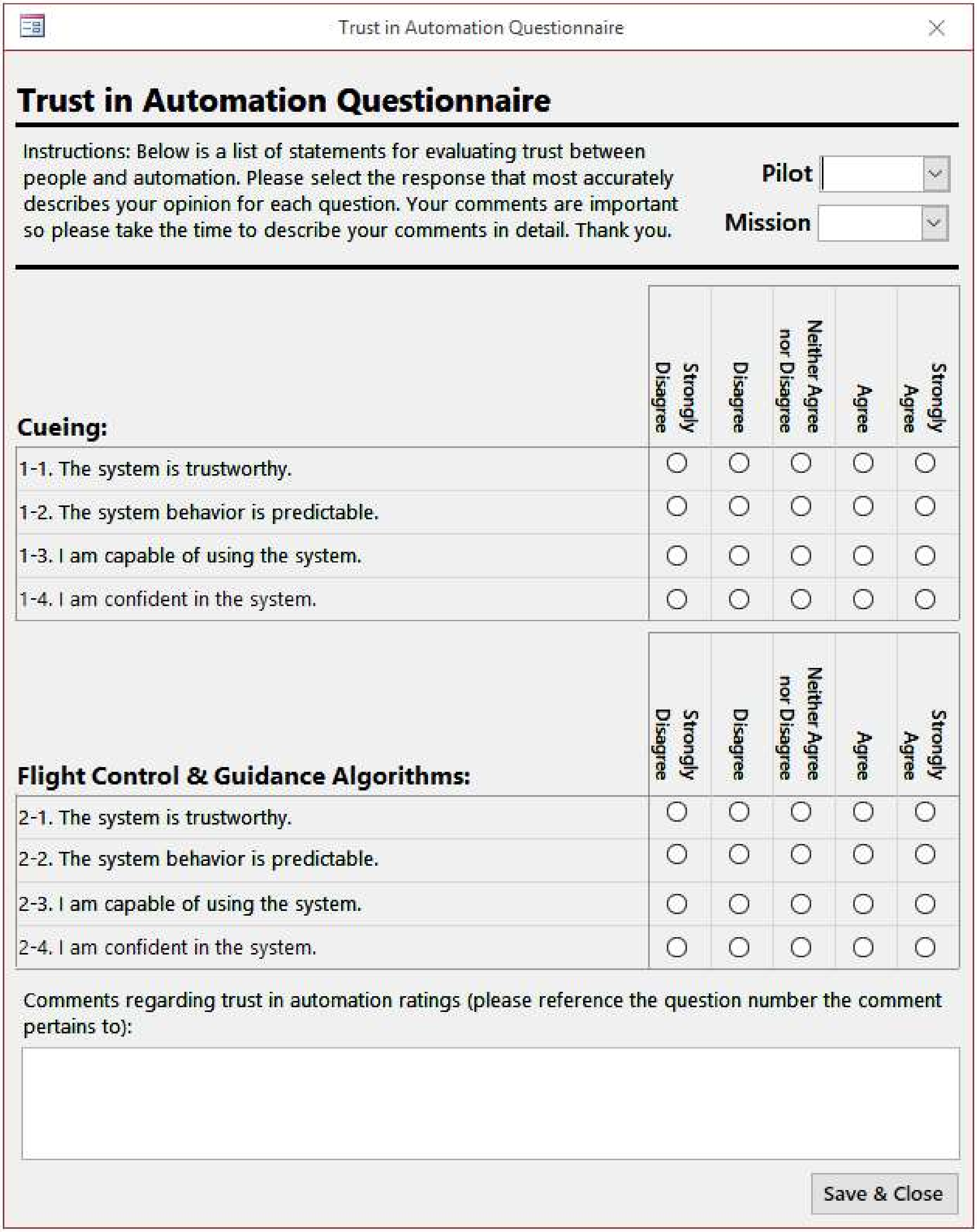
System Usability Scale (SUS)

Instructions: Read the following statements below and select you immediate response to each item, rather than thinking about it for a long time. If you feel that you cannot respond to a particular item, then select "neutral".

1. I would like to use the system to accomplish the mission..
2. I found the system unnecessarily complex..
3. I thought the system was easy to use...
4. I needed technical support to be able to use the system..
5. I found the various functions in the system to be well integrated...........................
6. I thought there was too much inconsistency in the system.......................................
7. I think that most pilots would learn to use the system very quickly........................
8. I found the system very cumbersome to use..
9. I felt very confident using the system..
10. I needed to learn a lot of things before I could use the system.............................

Save & Close

Figure D9. System Usability Scale.
Note. Participants were asked to use the drop-down menu to indicate Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree.



Trust in Automation Questionnaire

Trust in Automation Questionnaire

Instructions: Below is a list of statements for evaluating trust between people and automation. Please select the response that most accurately describes your opinion for each question. Your comments are important so please take the time to describe your comments in detail. Thank you.

Pilot

Mission

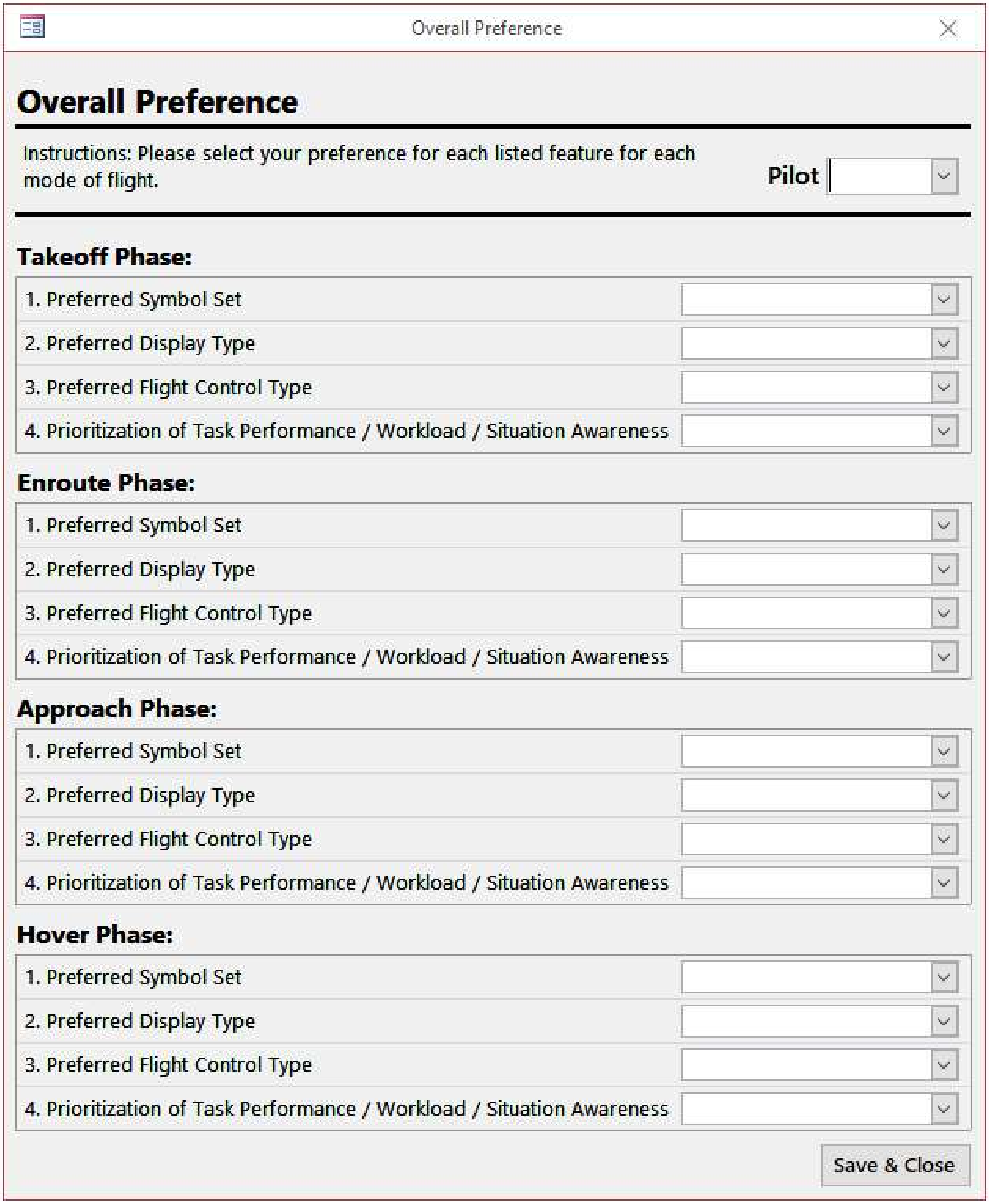
Cueing:	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
1-1. The system is trustworthy.	○	○	○	○	○
1-2. The system behavior is predictable.	○	○	○	○	○
1-3. I am capable of using the system.	○	○	○	○	○
1-4. I am confident in the system.	○	○	○	○	○

Flight Control & Guidance Algorithms:	Strongly Disagree	Disagree	Neither Agree nor Disagree	Agree	Strongly Agree
2-1. The system is trustworthy.	○	○	○	○	○
2-2. The system behavior is predictable.	○	○	○	○	○
2-3. I am capable of using the system.	○	○	○	○	○
2-4. I am confident in the system.	○	○	○	○	○

Comments regarding trust in automation ratings (please reference the question number the comment pertains to):

Save & Close

Figure D10. Trust in Automation questionnaire.



Overall Preference

Overall Preference

Instructions: Please select your preference for each listed feature for each mode of flight.

Pilot

Takeoff Phase:

1. Preferred Symbol Set
2. Preferred Display Type
3. Preferred Flight Control Type
4. Prioritization of Task Performance / Workload / Situation Awareness

Enroute Phase:

1. Preferred Symbol Set
2. Preferred Display Type
3. Preferred Flight Control Type
4. Prioritization of Task Performance / Workload / Situation Awareness

Approach Phase:

1. Preferred Symbol Set
2. Preferred Display Type
3. Preferred Flight Control Type
4. Prioritization of Task Performance / Workload / Situation Awareness

Hover Phase:

1. Preferred Symbol Set
2. Preferred Display Type
3. Preferred Flight Control Type
4. Prioritization of Task Performance / Workload / Situation Awareness

Save & Close

Figure D11. Overall Preference questionnaire.

Appendix E. Eye Gaze Tracker

Figure E2. Eye tracker, pupil/camera monitors, and control panel interface.

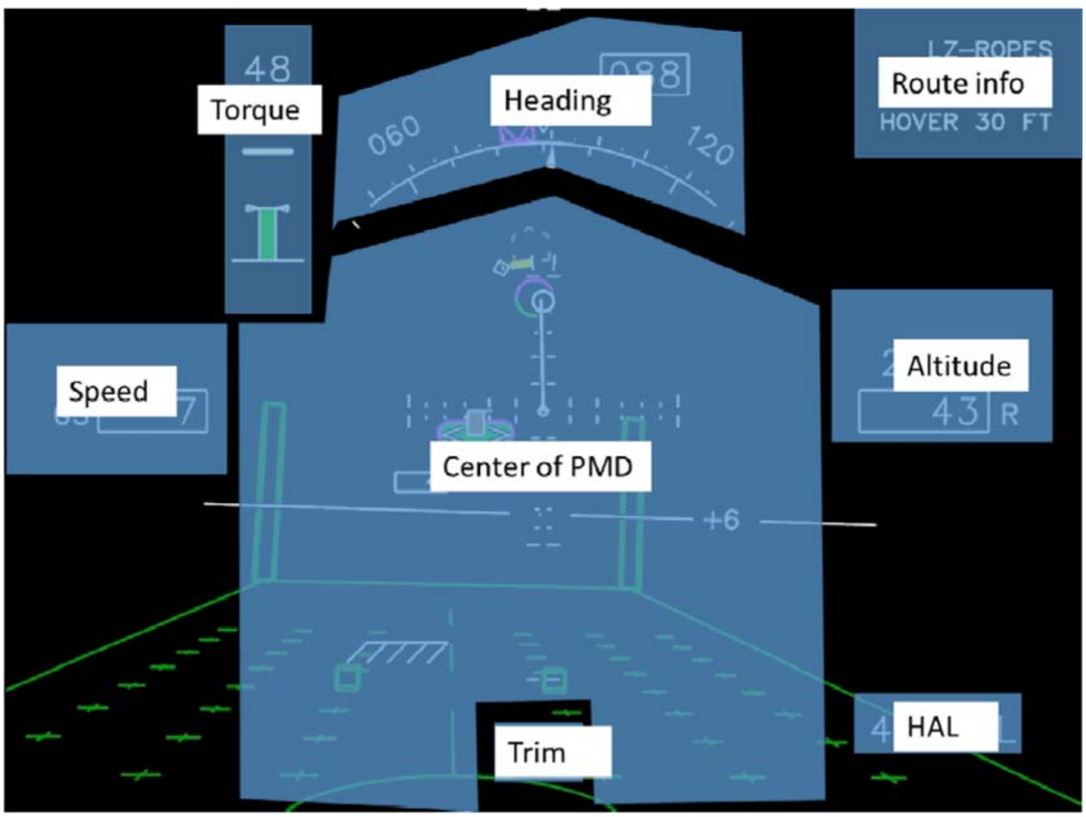


Figure E3. Symbology Set A Areas of Interest.

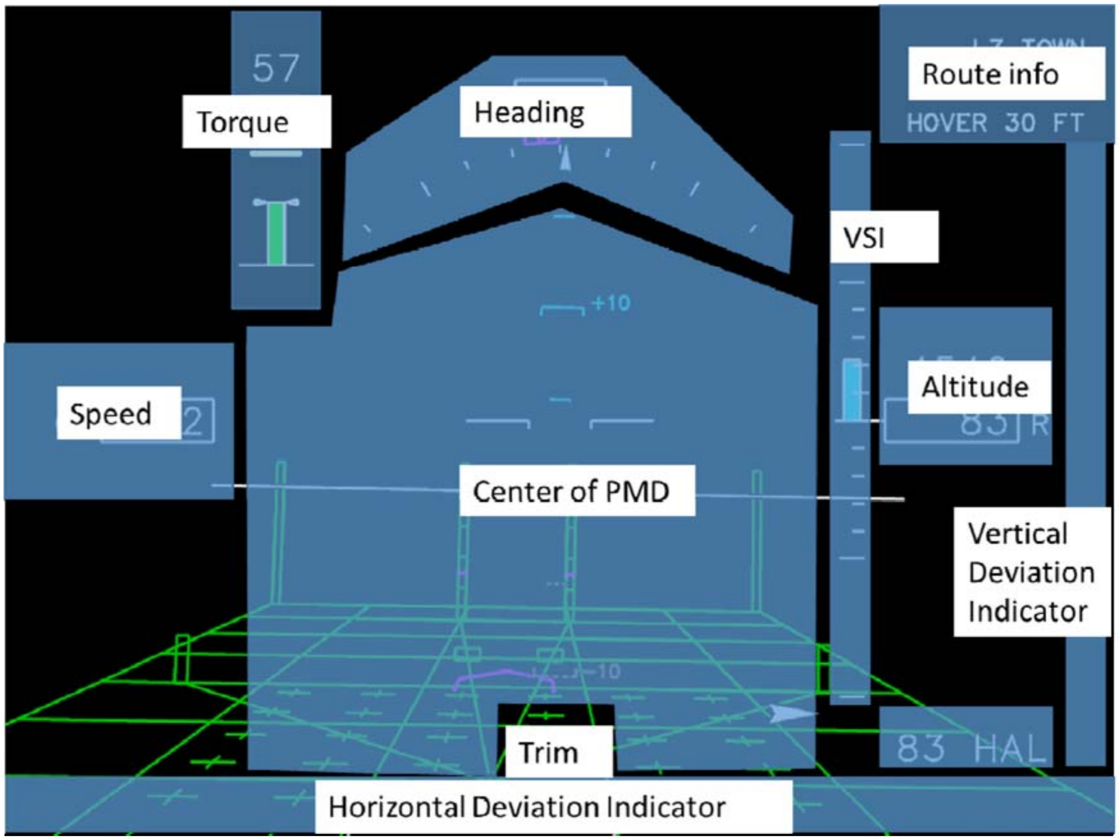


Figure E4. Symbology Set B Areas of Interest.

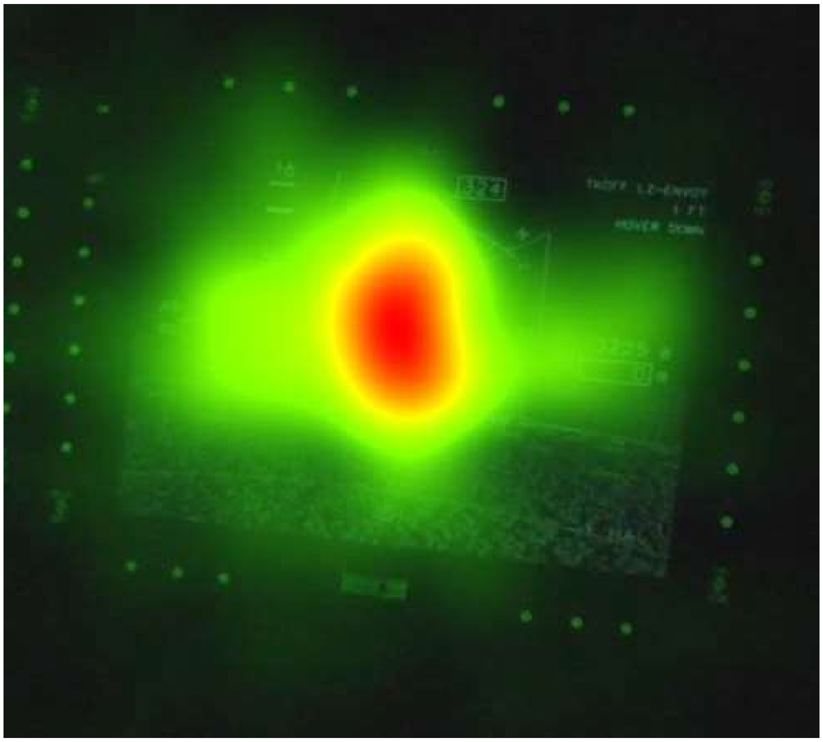


Figure E5. Takeoff Symbology Set A Heat Map.

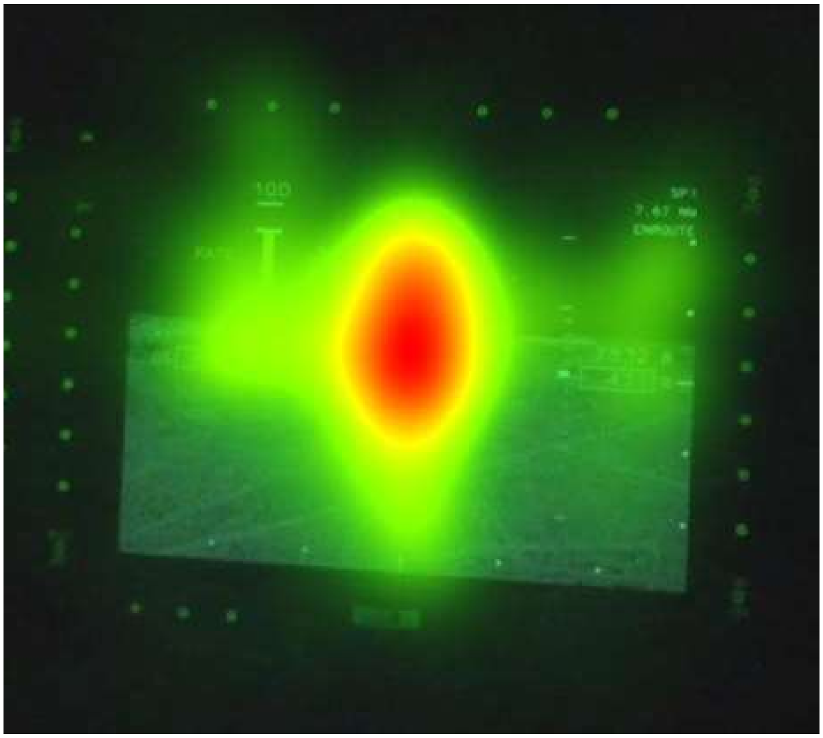


Figure E6. Takeoff Symbology Set B Heat Map.

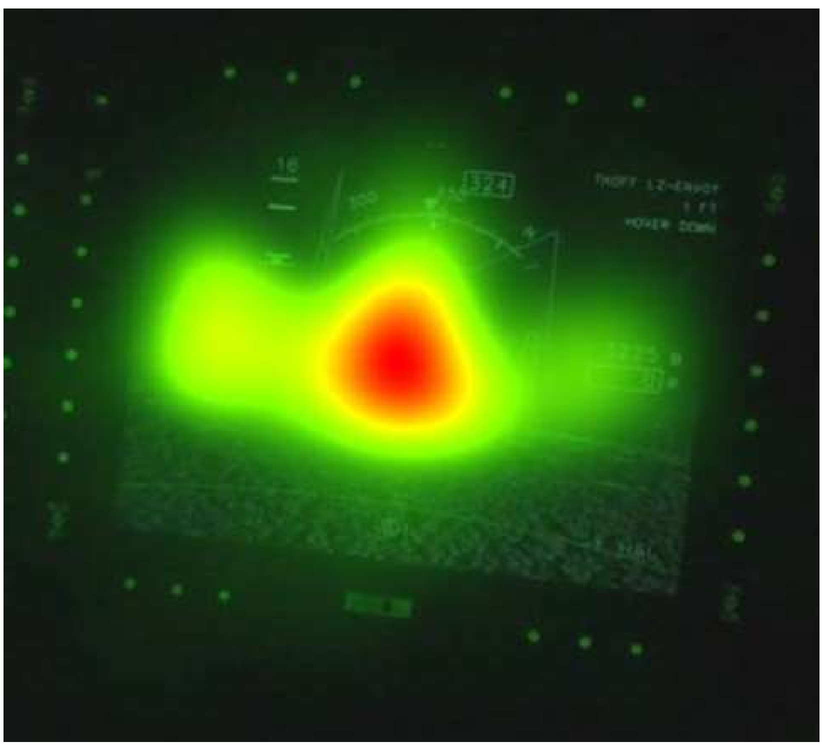


Figure E7. En-route Symbology Set A Heat Map.

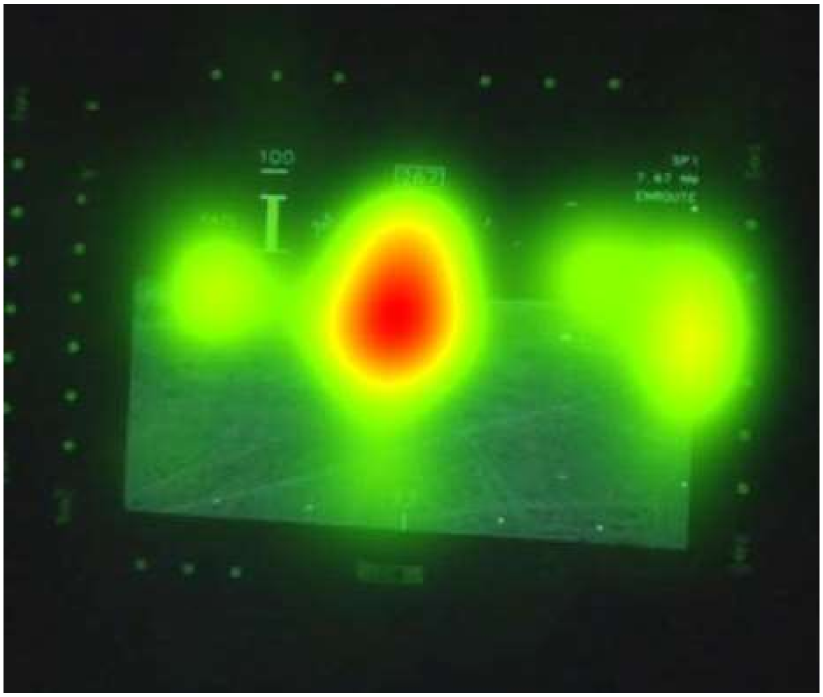


Figure E8. En-route Symbology Set B Heat Map.

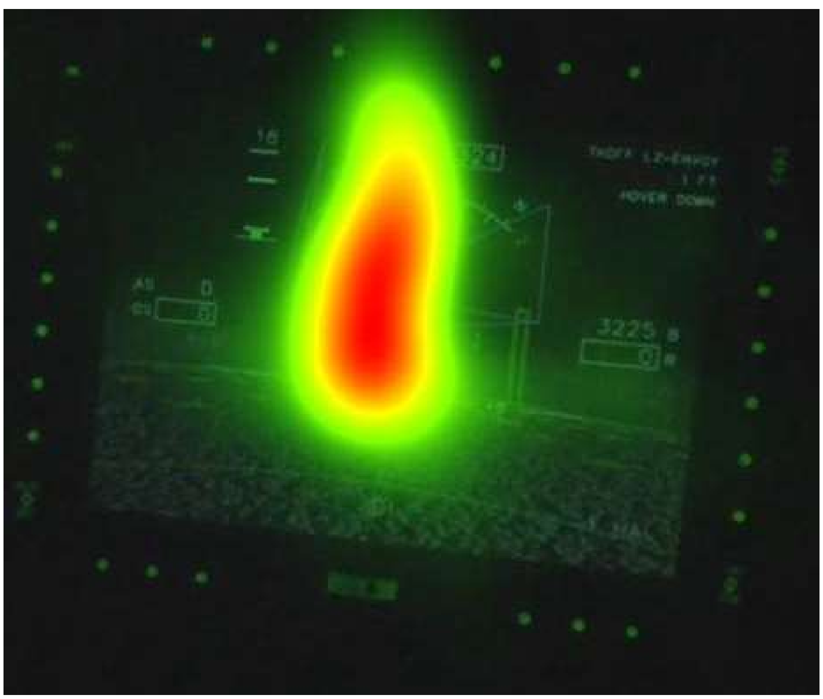


Figure E9. Approach Symbology Set A Heat Map.

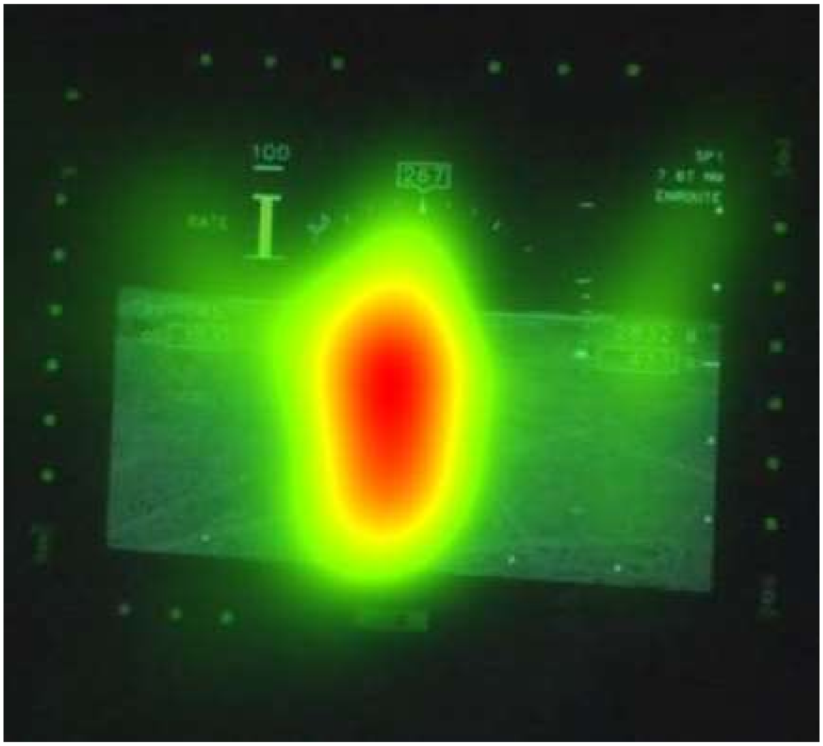


Figure E10. Approach Symbology Set B Heat Map.

Appendix F. Flight Performance Results Tables

Table F1. Approach Performance for the Main Effect of Symbol Set by LZ

	Symbol Set A		Symbol Set B				
	M	*SE*	*M*	*SE*	*F*	*p*	η_p^2
Base/Town							
Lateral Deviation (RMSD ft)	21.13	3.38	24.26	2.83	0.92	.370	.12
Heading Deviation (RMSD deg)	8.88	1.40	7.33	1.12	0.51	.500	.07
Speed Deviation (RMSD kts)	6.89	0.84	6.02	0.77	0.39	.555	.05
Envoy							
Lateral Deviation (RMSD ft)	29.69	2.94	51.91	3.87	38.09	.001	.86
Heading Deviation (RMSD deg)	11.18	4.06	12.59	2.70	0.07	.808	.01
Speed Deviation (RMSD kts)	5.28	0.53	8.26	0.55	16.10	.007	.73
Ropes							
Lateral Deviation (RMSD ft)	19.84	2.74	23.52	4.60	0.47	.470	.09
Heading Deviation (RMSD deg)	4.67	0.37	5.96	0.66	2.53	.163	.30
Speed Deviation (RMSD kts)	4.17	0.65	5.69	0.49	10.30	.018	.63

Table F2. Hover Performance for the Main Effect of Symbol Set by LZ

	Symbol Set A		Symbol Set B				
	M	*SE*	*M*	*SE*	*F*	*p*	η_p^2
Envoy							
Altitude Deviation (RMSD ft)	2.98	0.45	28.39	10.87	5.75	.062	.54
Heading Deviation (RMSD deg)	3.54	0.38	5.66	0.86	8.51	.033	.63
Radial Error (RMSD ft)	14.38	4.13	62.60	13.72	16.67	.010	.77
Ropes							
Altitude Deviation (RMSD ft)	3.18	0.47	4.80	0.62	3.39	.125	.40
Heading Deviation (RMSD deg)	4.26	0.37	4.78	0.83	0.34	.584	.06
Radial Error (RMSD ft)	5.11	0.97	8.51	0.64	8.33	0.034	.63

Table F3. Landing Performance for the Main Effect of Symbol Set by LZ

	Symbol Set A		Symbol Set B				
		SE	*M*	*SE*	*F*	*p*	η_p^2
Base/Town							
Lateral Speed (kts)	0.17	0.03	0.54	0.12	10.19	.019	.59
Heading Deviation (deg)	2.82	0.60	4.14	0.51	2.36	.168	.25
Radial Error (ft)	10.72	1.23	29.34	4.27	22.42	.002	.76
Envoy							
Lateral Speed (kts)	0.07	0.01	0.29	0.07	8.91	.024	.60
Heading Deviation (deg)	2.82	0.35	4.16	0.46	7.18	.037	.55
Radial Error (ft)	6.52	1.20	28.23	4.53	19.07	.005	.76

Appendix G. Biometric Results Tables

Table G1. Main Effects of Symbol Set En-route

	df	*F*	*p*	η_p^2
Base/Town				
Heart Rate Variability	1, 6	1.083	0.338	0.153
Heart Rate (beats per min)	1, 6	0.205	0.666	0.033
Respiration Rate (breaths per min)	1, 5	0.351	0.580	0.066
EEG Workload Index	1, 7	0.5	0.830	0.007
EEG Engagement Index	1, 7	0.009	0.926	0.001
Envoy				
Heart Rate Variability	1, 5	0.642	0.459	0.114
Heart Rate (beats per min)	1, 6	0.004	0.952	0.001
Respiration Rate (breaths per min)	1 ,6	1.26	0.305	0.174
EEG Workload Index	1, 7	0.09	0.772	0.013
EEG Engagement Index	1, 7	1.485	0.262	0.175
Ropes				
Heart Rate Variability	1, 6	1.517	0.264	0.202
Heart Rate (beats per min)	1, 6	0.021	0.889	0.004
Respiration Rate (breaths per min)	1, 5	0.496	0.513	0.09
EEG Workload Index	1, 7	0.772	0.409	0.099
EEG Engagement Index	1, 7	0.309	0.596	0.042

Table G2. Main Effects of Display En-route

	df	*F*	*p*	η_p^2
Base/Town				
Heart Rate Variability	1, 6	0.047	0.835	0.008
Heart Rate (beats per min)	1, 6	0.364	0.568	0.057
Respiration Rate (breaths per min)	1, 5	1.434	0.285	0.223
EEG Workload Index	1, 7	8.664	0.022	0.553
EEG Engagement Index	1, 7	0.631	0.453	0.083
Envoy				
Heart Rate Variability	1, 5	0.965	0.371	0.162
Heart Rate (beats per min)	1, 6	0.118	0.743	0.019
Respiration Rate (breaths per min)	1, 6	0.405	0.548	0.063
EEG Workload Index	1, 7	0.274	0.617	0.038
EEG Engagement Index	1, 7	3.011	0.126	0.301
Ropes				
Heart Rate Variability	1, 6	1.721	0.237	0.223
Heart Rate (beats per min)	1, 6	1.26	0.305	0.174
Respiration Rate (breaths per min)	1, 5	4.659	0.083	0.482
EEG Workload Index	1, 7	3.744	0.094	0.348
EEG Engagement Index	1, 7	1.216	0.307	0.148

Table G3. Main Effects of Symbol Set Approach

	df	*F*	*p*	η_p^2
Base/Town				
Heart Rate Variability	1, 6	0.719	0.429	0.107
Heart Rate (beats per min)	1, 6	0.006	0.939	0.001
Respiration Rate (breaths per min)	1, 5	0.267	0.627	0.051
EEG Workload Index	1, 7	1.637	0.241	0.19
EEG Engagement Index	1, 7	0.369	0.563	0.05
Envoy				
Heart Rate Variability	1, 6	0.009	0.926	0.002
Heart Rate (beats per min)	1, 6	0.350	0.576	0.055
Respiration Rate (breaths per min)	1, 6	0.341	0.581	0.054
EEG Workload Index	1, 7	0.014	0.909	0.002
EEG Engagement Index	1, 7	0.049	0.831	0.007
Ropes				
Heart Rate Variability	1, 5	0.699	0.441	0.123
Heart Rate (beats per min)	1, 5	0.094	0.771	0.018
Respiration Rate (breaths per min)	1, 3	0.263	0.643	0.081
EEG Workload Index	1, 7	0.026	0.877	0.004
EEG Engagement Index	1, 7	0.001	0.973	0.000

Table G4. Main Effects of Controls Approach

	df	*F*	*p*	η_p^2
Base/Town				
Heart Rate Variability	1, 6	4.174	0.087	0.41
Heart Rate (beats per min)	1, 6	5.639	0.055	0.485
Respiration Rate (breaths per min)	1, 5	0.112	0.751	0.022
EEG Workload Index	1, 7	6.514	0.038	0.482
EEG Engagement Index	1, 7	4.08	0.083	0.368
Envoy				
Heart Rate Variability	1, 6	0.001	0.979	0.000
Heart Rate (beats per min)	1, 6	0.001	0.980	0.000
Respiration Rate (breaths per min)	1, 6	5.724	0.054	0.488
EEG Workload Index	1, 7	12.322	0.010	0.638
EEG Engagement Index	1, 7	21.651	0.002	0.756
Ropes				
Heart Rate Variability	1, 5	5.726	0.062	0.534
Heart Rate (beats per min)	1, 5	3.903	0.105	0.438
Respiration Rate (breaths per min)	1, 3	0.003	0.962	0.001
EEG Workload Index	1, 7	0.191	0.675	0.027
EEG Engagement Index	1, 7	1.314	0.289	0.158

Table G5. Main Effects of Display Approach

	df	*F*	*p*	η_p^2
Base/Town				
Heart Rate Variability	1, 6	0.089	0.775	0.015
Heart Rate (beats per min)	1, 6	0.65	0.451	0.098
Respiration Rate (breaths per min)	1, 5	4.227	0.73	0.432
EEG Workload Index	1, 7	18.273	0.004	0.723
EEG Engagement Index	1, 7	0.012	0.917	0.002
Envoy				
Heart Rate Variability	1, 6	0.026	0.878	0.004
Heart Rate (beats per min)	1, 6	1.918	0.215	0.242
Respiration Rate (breaths per min)	1, 6	2.276	0.182	0.275
EEG Workload Index	1, 7	1.556	0.252	0.182
EEG Engagement Index	1, 7	0.003	0.956	0.000
Ropes				
Heart Rate Variability	1, 5	0.98	0.368	0.164
Heart Rate (beats per min)	1, 5	0.047	0.838	0.009
Respiration Rate (breaths per min)	1, 3	1.057	0.380	0.261
EEG Workload Index	1, 7	5.319	0.054	0.432
EEG Engagement Index	1, 7	2.245	0.178	0.243

Table G6. Main Effects Hover at Envoy

	df	*F*	*p*	η_p^2
Symbol Set				
Heart Rate Variability	1, 6	0.802	0.405	0.118
Heart Rate (beats per min)	1, 6	0.037	0.163	0.297
Respiration Rate (breaths per min)	1, 5	0.342	0.584	0.064
EEG Workload Index	1, 7	1.392	0.277	0.165
EEG Engagement Index	1, 7	0.661	0.443	0.086
Controls				
Heart Rate Variability	1, 6	1.627	0.249	0.213
Heart Rate (beats per min)	1, 6	2.534	0.163	0.297
Respiration Rate (breaths per min)	1, 5	0.289	0.614	0.055
EEG Workload Index	1, 7	4.580	0.070	0.396
EEG Engagement Index	1, 7	6.945	0.034	0.498
Display Type				
Heart Rate Variability	1, 6	2.775	0.147	0.316
Heart Rate (beats per min)	1, 6	0.002	0.966	0
Respiration Rate (breaths per min)	1, 5	5.746	0.062	0.535
EEG Workload Index	1, 7	6.604	0.037	0.485
EEG Engagement Index	1, 7	0.077	0.789	0.011

Appendix H. Training Questionnaire Comments

Below are comments that were provided on the training questionnaire:

- "The initial PowerPoint explaining the symbology was long, but I understand its necessity. It all really clicked when I saw a video though. I think (depending on the pilot's experience) a quick overview of the symbology set followed by a video of it all in action is a sufficient orientation prior to seeing it in action in the simulator."
- "The trainers were great in their instruction. I appreciated the more condensed symbology brief. Show me the symbols, show me the video. I like it."
- "I have to unlearn and change a lot of learned behavior. This is a good system but it would take time to learn and actually do a Fast rope mission."
- "Because I used the system the day before I was better. The sim is always a little hard to get used to. But I think that the training and the events should give good data as to the ability of a pilot to understand the system. I liked it and I can see a huge use in brownout or low vis. I would have loved to use it in Iraq and Afghanistan. I could have used it on 5 % of my missions (I mean that as a good thing. Those missions were the ones we were almost killed on)."
- "Training materials need to be updated in order to correspond with the current software in the simulator."
- "Ensure that presentation reflects symbology with all upgrades. Just double re-enforce the symbology that will be seen in the aircraft."
- "Trainers are excellent instructors and provided very thorough details to help with any issues."
- "Again, trainers were phenomenal and very helpful, made for easy training and helped me with any concerns or questions I had."

Appendix I. Motion Sickness Assessment Questionnaire

Comments provided on the MSAQ included:

- “Lots of eye fatigue, very irritable and annoyed especially using only PMD on set B.”
- “Last run with helmet mounted version, pilot felt pressure increasing on forehead.”
- “Any motion related feelings I felt were a result my eyes having to focus on the HMD. The close focus of it was causing a physical train on my eyes. I will attempt a better positioning and focus of the HMD foe the next iteration.”
- “A better focus and positioning was achieved than the previous iteration. Eyes did not begin to feel strained until the last leg of the flight, resulting in some minor stomach nausea.”
- “It took some extra effort to get my bearings during the takeoff phase due to navigating solely off of the screen in front of me.”
- “Although better, taking off was still disorienting, most likely due to the lack of proprioceptive cues. Familiarity with the system and the simulator response has mitigated some of the disorientation.”
- “My irritation came from lack of performance on the pinnacle approach. I failed to recognize my exact heading/position for a period. When I realized the issue, I now had to accomplish a much steeper approach.”
- “Although not a true problem with the HMD itself, I was finding it difficult to utilize the eye tracking glasses in conjunction with the HMD, resulting in some irritation about my ability to see the symbology.”
- “Ears hurt after a while.”
- “Whereas this mission was somewhat disorienting especially at LZ Envoy, it was not so disorienting to induce motion sickness.”
- “Felt fatigue start slightly setting in just from focusing intently.”

Appendix J. Bedford Workload Rating Scale Results and Comments

Table J1. Wilcoxon Results for Bedford Workload Rating.

	Flight Phase			
	Takeoff	*En-route*	*Approach*	*Hover*
Symbology *(Set A vs. Set B)*	N.S. Z = -1.227, p = .224	A < B Z = -1.964, p = .062	A < B Z = -2.129, p = .033	A < B Z = -2.877, p = .003
Display *(PMD vs. HMD)*	N.S. Z = -1.079, p = .293	N.S. Z = -0.765, p = .463	N.S. Z = -0.947, p = .379	N.S. Z = -0.745, p = .474
Flight Control *(SAS/FPS vs. MCCLAWS)*	N.S. Z = -1.564, p = .127	N.S. Z = -0.423, p = .721	N.S. Z = -0.737, p = .489	N.S. Z = -0.782, p = .461

Note. Results are color coded green for significance (p < .05). "N.S." is used to indicate no significance.

General comments on the Bedford Workload Rating Scale include:

- "With the level of experience I have with this system, it is all that I have in me to just keep the greasy side down. I would not be able to conduct any other tasks while doing this."
- "En-route workload was low."

Comments on the Bedford Workload Rating Scale related to Symbology Set A include:

- "Overcontrolling during hover mode was significantly reduced through use of velocity vector and circle."
- "I felt that in all phases except for en-route if I attempted to shift focus between terrain and symbology I would begin to drift off of the system cues."
- "Symbology was divided into areas that required large scan."
- "Takeoff workload was lower now that I am used to the symbology. Still scanning for the information but getting quicker."
- "More difficult all around on this iteration... Struggled with aircraft yawing without input on pedals during en-route phase. Also experienced difficulties maintaining position within the corridor box."

Comments on the Bedford Workload Rating Scale related to Symbology Set B include:

- "Hover takes a bit more focus because I am reacting to the 3d symbology cues around me. My workload during the approach was more manageable because I was able to use the anticipator to represent my circle of action and allow myself to fall back on the fundamental skills used during an approach, as opposed to following symbology."

- "There was additional workload for me during the phases where attitude is most important. During takeoff, I initially had trouble determining which direction I was traveling because the ground speed read a number, but I was unsure of which direction because"
- "Hover workload is high due to reduced cueing. Visual only with a small field of view is difficult. At a hover, I believe a traditional velocity vector would be extremely beneficial when the hover point is selected."
- "Hovering is still difficult when using the system's visual references. During the last hover near the buildings, however, I was able to hold a much more stable hover compared to the other ones utilizing a combination of strictly the sensory and tactile cues."
- "En-route contour lines would help."
- "Most of the workloads experienced was having to scan large areas to find and interpret the information presented."
- "Workload is reduced with symbology set B."
- "All workloads were manageable with symbology set B."
- "Approach is definitely the highest workload especially as the aircraft comes close to the LZ. Following the symbology coupled with the quirks of the simulator versus a real aricraft makes it challenging enough, but not to the point of stress overload."
- "Approach still the most difficult, workload wise, simply trying to correlate what is being viewed with control touch."

Comments on the Bedford Workload Rating Scale related to control type include:

- "With the collective not coupled, it was harder to focus on any other tasks at hand."
- "Only slightly difficult with MCLAWS."
- "Approach workload was reduced significantly with the collective coupled."
- "The simulator does not react like the aircraft and having the system adjust the collective for me was beneficial."
- "Most of the workload during takeoff came from keeping the aircraft under control. Once the initial movements were compensated for, the workload rating improved significantly."
- "Coupling the collective greatly reduced my workload and offered more opportunities to pay attention to external surroundings and other cockpit indications."
- "Could be just simulator, but the most difficult part is coming straight up."

Comments on the Bedford Workload Rating Scale related to display type include:

- "I would still prefer having the goggles attached so I can scan by moving my head rather than looking directly in front to see the PFD."

Appendix K. Situation Awareness Rating Scale Results and Comments

Table K1. Wilcoxon signed rank tests of internal SA ratings

	Flight Phase			
	Takeoff	*En-route*	*Approach*	*Hover*
Symbology *(Set A vs. Set B)*	N.S. Z = -0.073, p = .961	A < B Z = -1.868, p = .064	A < B Z = -2.149, p = .031	A < B Z = -2.921, p = .002
Display *(PMD vs. HMD)*	N.S. Z = -1.734, p = .102	N.S. Z = -0.109, p = .900	N.S. Z = -0.643, p = .550	N.S. Z = -1.091, p = .296
Flight Control *(SAS/FPS vs. MCCLAWS)*	N.S. Z = -1.237, p = .240	N.S. Z = -0.593, p = .681	N.S. Z = -0.613, p = .587	N.S. Z = -0.551, p = .619

Note. Results are color coded green for significance (p < .05). "N.S." is used to indicate no significance.

Table K2. Wilcoxon signed rank tests of external SA ratings

	Flight Phase			
	Takeoff	*En-route*	*Approach*	*Hover*
Symbology *(Set A vs. Set B)*	N.S. Z = -1.113, p = .280	N.S. Z = -0.744, p = .499	A < B Z = -1.840, p = .066	N.S. Z = -1.361, p = .173
Display *(PMD vs. HMD)*	N.S. Z = -0.633, p = .535	N.S. Z = -1.277, p = .215	N.S. Z = -0.394, p = .706	N.S. Z = -1.055, p = .303
Flight Control *(SAS/FPS vs. MCCLAWS)*	N.S. Z = -0.065, p = .869	N.S. Z = -0.881, p = .402	N.S. Z = -1.217, p = .238	N.S. Z = -0.958, p = .364

Note. Results are color coded green for significance (p < .05). "N.S." is used to indicate no significance.

Open-ended comments regarding internal SA include:

- "Internal situational awareness in all modes are still a little less but getting better. I don't know how much I could do as a PC today with the system but I think I would get much better."

- “As I mentioned during the flight, the attitude indicator in the goggles is not attached to the 2d symbology. I found myself searching for the attitude references during all phases of flight. We fly attitude and power settings. I search for a specific power setting and attitude for each specific phase of flight. (ie. Wings level, Q set at 46% for cruise flight at 100 KIAS at 15,700 lbs, or 5 degrees nose up at 38% Q for 80KIAS).”

Open ended comments regarding external SA include:

- “The information is great but you have very little concept of terrain or other traffic in your vicinity.”
- “Following the symbology at a hover prevented me from visually avoiding obstacles, I was wholly trusting the system.”
- “External SA took a major hit due to the reduced visibility of a single screen. It had to be compensated for with internal SA.”
- “Work load was high during takeoff and landing/hover. I was too busy concentrating on the data rather than the external environment.”
- “The corridor symbology was also not distinct enough to indicate a climb or descent until time to make the inputs.”
- “Without the ability to scan, my situational awareness was degraded. I was unable to see anything except what was in front of me.”

Appendix L. Cueing Usability Results and Comments

Table L1. Wilcoxon signed rank tests of cueing usability ratings

	Flight Phase			
	Takeoff	*En-route*	*Approach*	*Hover*
2D Symbology *(Set A vs. Set B)*	**A > B** Z = -2.993, p = .002	**A > B** Z = -4.300, p < .001	**A > B** Z = -3.611, p < .001	**A > B** Z = -4.118, p < .001
Guidance Symbology *(Set A vs. Set B)*	**A > B** Z = -3.463, p < .001	**A > B** Z = -3.882, p < .001	**A > B** Z = -3.087, p = .001	**A > B** Z = -4.170, p < .001
3D Conformal Symbology *(Set A vs. Set B)*	**A > B** Z = -4.134, p < .001	**A > B** Z = -4.183, p < .001	**A > B** Z = -3.719, p < .001	**A > B** Z = -3.376, p < .001
Sensor Visualization *(Set A vs. Set B)*	A > B Z = -1.882 p = .086	N.S. Z = -1.597, p = .121	**A > B** Z = -2.063, p = .044	N.S. Z = -1.521, p = .120
Aural Cueing *(Set A vs. Set B)*	**A > B** Z = -2.133 p = .037	N.S. Z = -1.606, p = .121	N.S. Z = -1.560, p = .150	N.S. Z = -1.144, p = .267
Tactile Cueing *(Set A vs. Set B)*	**A > B** Z = -2.610, p = .010	**A > B** Z = -4.108, p < .001	**A > B** Z = -2.951, p = .003	**A > B** Z = -2.209, p = .035

Note. Results are color coded green for significance (p < .05). “N.S.” is used to indicate no significance.

Table L2. Wilcoxon signed rank tests of aircraft controllability ratings

	Flight Phase			
	Takeoff	*En-route*	*Approach*	*Hover*
Controllability of Aircraft *(SAS/FPS vs. MCLAWS)*	N.S. Z = -1.431, P = .210	N.S. Z = -1.414, P = .241	N.S. Z = -0.406, P = .750	N.S. Z = -0.881, P = .502

Symbology Set A comments include:

- "It was difficult to determine aircraft attitude without the use of the 2d symbology, resulting in a lot of drift during the takeoff phase."
- "I found it very difficult to maintain heading and position during the takeoff phase."
- "I was unable to utilize the cues available to me in order to hover and takeoff without drifting on a consistent basis."
- "Much easier in all aspects with Symbology set A, than B."
- "TQ warning drew my attention within a second. Great."
- "There was plenty of time to learn the symbology and analyze the data."
- "I mentioned that we teach students to focus on pitch and power settings in order to achieve a certain flight profile. I found myself focusing on the flight path prediction indicator instead of my attitude indicator. The attitude indicator was covered up by the flight path prediction indicator drawing my focus away from the attitude indicator as well as obscuring the information that was vital to each flight profile. Perhaps increase intensity or the color of the attitude indicator in order to bring a pilot's focus back to it. I would also like to make the attitude indicator a part of the 2d symbology so I do not have to search for the attitude indicator. When flying the Heads up display on the UH-60, the heading and the attitude are all combined."
- "I was having issues getting the guidance symbology (for my deceleration) bringing me to my hover or landing point when I maintained my velocity vector within the pink/green circle (I always seemed to overshoot). When I slowed down and left myself short of the pink half circle, I was better able to achieve my landing area."
- "Information overload for the first flight. Trying to take in and analyze the various cues that are available."
- "My only complaint is that the speed cue for the approach was so far forward that I had to tilt my head down to use both visual and digital cues."

Symbology Set B comments include:

- "The green LZ grid lines are crucial for hovering and takeoff."

- "As previously mentioned, I had issues determining my exact direction of drift at takeoff until it became significant enough. I found myself trying to reference the sensor visualization more because it had more reference points closer to the ground. Once airborne, I was able to shift focus to the 3d symbology."
- "The sensor visualization is difficult to use with the 3d overlay. If detected, an obstacle could be highlighted in a different color to differentiate between safe areas and ones with obstacles."
- "It is difficult to determine drift when there is a lack of ground references when utilizing the sensor visualization. I tried to use a block of pixels during takeoff, was unable to. A big contributor to my drift at takeoff is my inability to see my rotor disk. I am just guessing at where it is based on my cyclic position, and am only starting to get used to the nuances of the simulator."
- "Hard to determine accurate pitch attitude while using 2d symbology as well as drift."
- "There was really no takeoff symbology that was useful to combat drift in the B set."
- "Slightly more difficult on takeoff, especially with focusing on symbology, as opposed to outside, but quite taxing."
- "Difficulty follow or adjusting pitch and power for flight path marker."
- "Although for the most part good, the 3d conformal symbology was lost when the route entered undulating terrain as portions of the route were lost behind obstacles. The anticipator and airspeed indicator are great for helping me keep altitude and airspeed. During turns, however, when the anticipator and the wings are separated, I find myself reverting to basic piloting tendencies. i.e. I notice the > is slightly below the anticipator, indicating that I am slowing down. In order to get it to return to the middle, my initial reaction is to pull back to bring it up. Once the > as a result of my actions, I realize and fix my control input."
- "2D: I had issues with the vertical deviation indicator, mostly because it is reactive in nature. I could not truly anticipate altitude changes aside from my best guess based upon the sensor visualization. This resulted in me being behind the aircraft as I transitioned into the approach phase, thereby affecting my approach. I rarely referenced the horizontal deviation bar because I had the ground track. When using this particular flight path symbology I would not use it to go through the mountains, so I am less concerned with maintaining a perfect ground track."
- "Guidance symbology: the cyan flight path marker continues to be useful and I like the methodology of indicating a need for an airspeed change, aside from getting occasionally confused on what the > actually indicates (accel or decel and what control input is needed). I do think the scale should be expanded in the HMD. It is harder to see where the > is in relation to the cyan bar because it is smaller in the HMD."
- "3D: I do not like how I lose the ground routing reference due to undulating terrain."
- "2D: The vertical deviation scale is reactive to my current position and would be better if an anticipated altitude could be shown as well, allowing for better power management and sequence of event timing during climbs and descents. I would want to maintain close

proximity to the ground to avoid detection, but there are times that I do not realize that the ground descends. Although the vertical deviation scale is nearly identical to the ILS symbology in the UH-60M, there is some level of mental conversion going on as a switch from visual cues to the scale, resulting in a slight delay in control input. I don't think I looked at the horizontal deviation scale at all."

- "3D: I like the idea of the route overlay on the ground, but I do not like losing it in undulating terrain."
- "The vertical and lateral guidance indicators are too far outside of the normal scan. Suggest brining the indicators closer if not inside of the VSI and trim ball. Would also like to have more tactile cueing due to the hard to interpret guidance cues."
- "The track symbology was only good for lateral guidance. Unless a pilot has studied the route, there would be no early indication of rising terrain. The FLIR image was not good enough for the pilot alone to analyze the terrain properly."
- "Would like to have the tactile cueing during the en-route phase."
- "En-route symbols easy to follow, easiest, compared to T/O and Landing."
- "Not a fan of the 3D goal posts, free standing box may be better…"
- "ACP "Goal Posts" very difficult to see. "Breadcrumbs" very useable."
- "The cyan flight path marker allows me to make my approach and look at other aspects of the screen. During one approach, my anticipator was right in my landing area, but I realized that I would have impacted a mosque because I was able to scan the FLIR imagery."
- "I like the more free-form approach style that this symbology allows, but I feel there is a deficiency in determining my attitude, as previously mentioned. If a bar that gives my numerical attitude like in symbology set A could pop up during the mid-phase of the approach, I believe I would perform better."
- "I like the more standard approach angle as opposed to the parabolic curve of symbology A."
- "The flight path marker was more usable for airspeed control in B set symbology. Airspeed references are easier to set with these indications."
- "No additional comments to previous surveys. All comments remain the same."
- "The airspeed predictor was beneficial on the flight path marker."
- "Much more difficult to control the aircraft on approach, tended to drift if not 100% focused on symbology."
- "Approaches still difficult but more manageable."
- "I recognized drift more from the 3d conformal symbology than the chevron guidance. The chevron mostly gave me an aiming point but could be more precise. I found it difficult to maintain a stable hover and detect minute changes in my drift."
- "Guidance: due to the more compact nature of the HMD screen, it is difficult to determine smaller amounts of drift when referencing the white/pink chevrons. Despite seeing the white drift away from the pink, I had issue correcting the drift because I had to

shift my gaze so far in order to determine my actual attitude. I was trying to maintain my normal hovering attitude, but I couldn't determine my pitch and roll without shifting focus (via head movements instead of a quick eye glance) away from my ground reference."

- "The white chevron and pink chevrons are difficult to align, resulting in a lot of drift. I try to utilize the 3d overlay to compensate, but still have a rough time. A velocity vector would help."
- "I find I don't use much of the 2d symbology, save for the torque. I try to use the attitude indicator but it is hard to watch references and turn my head to see it."
- "Guidance: The white/pink chevrons are still difficult to align, especially with the smaller HMD screen."
- "The severity of the bank and pitch attitudes do not correlate to the attitude indicator. Would like to see the same cues from the artificial guidance as is displayed on the attitude indicator."
- "Again, drift was difficult to determine with the current attitude indications."

Comments regarding HMD include:

- "Both approach and hover phases benefited from using the HMD. I was able to look at my LZ and fly the aircraft visually while referencing the cues give from the system."
- "The attitude of the aircraft in the HMD is not the same as the attitude in the PMD."

Comments regarding sensor visualization include:

- "Sensor visualization is only good directly in front of the aircraft. Using the PMD limits the visibility to properly scan for hazards."
- "Once again the strong focus on the 2d symbology prevented significant sensor use. I was more focused on the symbology in order to hover, as it is difficult to develop a good sight picture."
- "As I become familiar with the symbology sets, I am better able to check my surroundings for obstacle avoidance."
- "The sensor visualization works well when there are significant obstacles nearby to use as a reference point."

Comments related to aural cueing include:

- "There was one takeoff where I distinctly heard the aural altitude cueing during takeoff. I did not hear it during the others, however. I'm unsure if it was occurring during the previous iterations of the flight (possibly due to getting used to the symbology). I found the aural cueing to be very beneficial during my takeoff sequence…alerting me to achieving 50 ft and indicating when to initiate my acceleration.”

- “When available, the aural cueing helped my sequence of actions during takeoff.”
- “Aural cueing almost not useful on T/O simply because of focus on the task of coming straight up and also reaching desired attitude and altitude.”

Comments related to tactile cueing include:

- “Paid more attention to tactile cueing especially in flight when speed got to slow or to fast.”
- “Tactile cueing almost not useful on T/O simply because of focus on the task of coming straight up and also reaching desired attitude and altitude.”

Comments related to flight controls include:

- “ITO seemed easier with SAS/FPS vs MCLAWs.”
- “Having the collective coupled improved the controllability of the aircraft while at a hover.”
- “Having the collective coupled allows me to focus on the speed and drift of the aircraft. I would prefer to have the collective coupled when only utilizing the PFD as my primary means of navigation and scanning.”
- “SAS/FPS Much easier”

Additionally, the following open-ended responses were collected upon completion of all missions in each symbology type (set A and set B) for the following cueing features:

Comments related to 2D Symbology (Set A) include:

- “The symbology was very helpful in assisting with situational awareness. As the iterations progressed, I was actually able to pay more attention to the information input I was receiving. The first iteration was information overload. A declutter option would be nice.”
- “Very easy to follow during hover.”
- “No issues.”
- “No issues.”
- “Overall the 2d symbology was straightforward and easy to use. I felt that the velocity vector was sometimes too sensitive during hover and made me feel like I was drifting more than I was. As I became accustomed to it and understood the scale (1-2 knots close to the crosshairs) I felt that I was improving.”
- “Helped me know the info I needed though all phases.”

- “Useable, but not required or focused on when utilizing the Guidance and 3D Conformal symbols.”

Comments related to 2D Symbology (Set B) include:

- “The 2D symbology was excellent in in set B in all modes of flight.”
- “Liked the minimal approach. What was needed to fly the aircraft without extra input.”
- “Easy to use, but I did not find myself using it very often as it was difficult enough to hover.”
- “Attitude indicator was too elongated on the HMD and difficult to find pitch attitude reference in a timely manner during cross-checks.”
- “Overall the 2d symbology was useful with the exception of the vertical and horizontal deviation scales. I rarely looked at the horizontal deviation bar. The vertical bar was reactive in nature and I had difficulty anticipating the route climbs and descents. I believe an anticipator would help with that. I also had a slight delay in control input as I changed my thought process from visual flying to interpreting what is essentially my ILS glideslope. When using the ILS as my sole navigation source it is not an issue, but only when switching back to it many times per minute.”
- “Change ft and NM to KM or have the ability.”
- “2d symbology was good. It was lacking the attitude indicator that is attached to the 2d information. The addition of an artificial horizon to the attitude indicator which looks similar to the attitude indicator would be beneficial to situational awareness. Drift could be determined more effectively with a better attitude indicator. I found myself referencing the attitude indicator to maintain my position at a hover.”
- “Symbology with system is similar in use to the M Model H-60. Very useable. Scanning technique is similar. I have no issues using the 2D symbology.”

Comments related to guidance Symbology (Set A) include:

- “Much like the 2D symbology, the guidance helped as well. The velocity vector for horizontal situation awareness was tricky to learn. The glide slope is more difficulty. Obvious it doesn’t behave like an airport glideslope where you can set your initial decent rate and pretty much forget it. This changes constantly, which requires keeping it in your scan. Not sure if I like that feature or not, but of course when its coupled which the collective, its awesome.”
- “Easy to use.”
- “The corridor cue in set A was improved due to a complete visualization of corridor height and width.”
- “The guidance symbology did a great job during the approach phase helping me to keep my speed and altitudes under control. The cyan anticipator was extremely helpful during the enroute phase in helping me maintain a good course line throughout the turns and

during the approach phase. I found the 'wings' that indicated my speed deviations to be helpful, but I found myself referring to the digital groundspeed indicator to back myself up. During the transition phase between takeoff and landing, I spent more time than I would have like transitioning from a digital readout that gave me my pitch attitude to the pitch indicator/wings combination. This was in part due to the brown lettering of the negative pitch values and the tan sensor visualization. This could be mitigated in my case if I had the digital pitch value available for a longer period of time."

- "Excellent. Once I understood how to use the info I really liked it. Easy learning curve."
- "Much prefer the corridor in the sky to Symbol Set B. Still not a fan of the ACP "Goal Post" with the vertical lettering. Perhaps utilizing a highlighted box in the sky to denote this might be better. Was very impressed with the guidance during approach giving cues to where the collective and cyclic should be. Whereas this makes it "dummy-proof" and not for "free-flght" mode, this definitely has its application in the tactical arena."

Comments related to guidance Symbology (Set B) include:

- "I did miss having the velocity vector that was in set A. Otherwise, set B had enough information, and not too much."
- "Easy to follow, as the test progressed it was intuitive to look at and see the point."
- "Guidance symbology is easy to use. In particular, I really like the depiction of SP/ACP/RP. I prefer the SET A routing symbology as it clearly defines the lateral boundaries of the route to be flown."
- "The flight path marker became unusable for me at times due to it rising into the top 1/3 of the screen. Although pitch remained constant, the cue would track significantly up when power was applied. My eyes were in a fixed scan toward the horizon and flight path, not in an upward velocity. Therefore, the pitch cues were lost at times."
- "The cyan flight path marker is very useful and I like the method of indicating groundspeed deficiencies, but the groundspeed chevron and scale could be slightly larger for ease of reading. The chevrons during hover give a good marker but are difficult to keep aligned. I found the altitude markers during a hover (the pink on the green towers) only somewhat useful. I glanced at them once or twice, but often started drifting as I took my attention from the center of the screen. A velocity vector in the center of the screen would be very useful at a hover."
- "FPM rolling off of the screen makes it hard."
- "The lateral guidance was good but I preferred the guidance of symbology A. Following a corridor is easier than trying to follow a set of arrows while looking at the extreme right of my scan sector to determine altitude and at the bottom for lateral deviations. The addition of the tactile sensors to the enroute phase would add to the successful flight of the corridor."
- "Love the "breadcrumbs" depicted on the ground for the route. Not a fan of the ACP "Field Goals" They are difficult to see and are very thin. Also utilizing the HMD display,

not all of the ACP name/ information is shown; granted this information is available on the 2D symbology/ information in the top right. On Take off, the breadcrumbs are almost impossible to see therefore, if the aircraft is not oriented in that direction, unless you pick up and orient to find the symbols, you may not know where they are."

Comments related to 3D conformal Symbology (Set A) include:

- "Good information contained, but perhaps the last thing I truly got used to scanning. By the end of session, I was very comfortable including the 3D symbology in my scan."
- "Easy to stay on route, easy to visualize ACP/RP/SP, etc."
- "Set A cueing for approach and hover was much improved over set B. In particular the pitch change cue and collective cue made for simplistic guidance that I was able to follow with minimal practice. Furthermore, the symbology did not cause over controlling or guess work to maintain a stable hover."
- "I thought the 3D conformal symbology was incredibly helpful. The route guidance was enroute was great and the landing zone indications were amazing. I feel that I would have had a lot of issues landing exactly where I intended without them."
- "Loved it. I could see what was coming up."
- "Not a huge fan of anything ground based extending skyward, because, whereas they are only digital objects (like goal posts on the approach square) I feel they are interpreted by the brain to be something to avoid (like a tower) and therefore influence control movements. Once suspended in the air, however, it makes for easy cueing."

Comments related to 3D conformal Symbology (Set B) include:

- "The 3D symbology was better in set B than A. I especially liked how the landing field built with grid lines and reference towers."
- "Very much liked the flight path chevron and gates to pass through for course guidance... Might have been task saturated, but never looked at distant hover grid furthest forward towers for reference altitude."
- "The hover overlay is useful in detecting drift. I like the idea of the ground overlay for the route but am worried that it will disappear in mountainous terrain."
- "Add colors."
- "Great addition which helps determine altitude and position in an LZ."
- "On the approach and hover 3 D Conformal Symbology, I am not a fan of the gridded box. The white and purple chevron is easy to understand and align, though it takes getting use-to. The HMD is also very sensitive. Any slight movement of the head and it is extremely shaky, whereas I was able to overcome this initially, I could see where some people could get disoriented."
- "Difficult to maintain a hover position when trying to line up the 2 chevron. A velocity vector might be beneficial to indicate immediate drift direction."

Comments related to sensor visualization include:

- "I like how you can see through the airframe, that is extremely helpful. However, I am way too inexperienced to fully appreciate the sensor visualization. Again, it's information overload right now, and I cant look past the symbology to appreciate what it offers yet. But, by the end of the training session, I was able to use this asset more, and was able to focus more "outside" the aircraft, as opposed to just the HMD/PMD information."
- "Wasn't able to adequately utilize until a few flights in with the symbology set. First several approaches were heavily focused on the symbology with minimal crosscheck on the FLIR image"
- "Imaging was clearer on the MFD vs HMD. Symbology was blurry on outer edges during Helmet mounted version."
- "The sensor visualization was good when using the HMD, but I found myself ignoring it in favor of the symbology. I don't doubt that my focus would be allowed to shift as I became more familiar with the system. When using only the screen, I didn't feel it was as useful, but that was primarily due to the limited field of view."
- "The sensor visualization is becoming more useful as I become more familiar with the symbologies in general. Additional familiarity allows me to scan outside more and detect obstacles."
- "Really good."
- "PMD was lacking for sensor visualization. The HMD offered better situational awareness during all phases of flight."
- "Positioning of the "Camera" or FLIR is difficult to get used to simply because it is so low to the ground. If this could be improved to being mounted closer to the eye position (height) of the pilots, I think it would help immensely."
- "With the digital information being fed to the pilot, and understanding that I have zero time dealing with the system, I feel that the sensor visualization (i.e. FLIR) gets faded out by the brain, almost as if the ground wasn't even there, as if it would not."

Comments related to aural cueing include:

- "I liked the aural cuing. A separate control panel, or integration into the FMS so I can opt out of the aural cueing would be nice."
- "Aural cueing was excellent as in Set A."
- "The audio cueing felt relevant without being overwhelmed w/ information."
- "Did not feel excessive or overdone. Did not consider a distraction."
- "Variance in volume, sometimes the lady's voice was very loud. Sometimes sounds easy to understand, sometimes sounds too electronic like the old UH-60 APR-39 guy. I don't know that constant altitude cues on takeoff are necessary like they would be on approach."

- “The aural cueing is annoying when given in 10ft increments. It is less necessary on takeoff than it is on landing. Would prefer for the vocals to be cleaned up to sound less electronic. The "airspeed set to XXX knots" tape is a little hard to understand, especially when the senses are already loaded up with trying to take off.”
- “No issue with aural cueing.”
- “Cueing was good. When cueing to adjust speed to 80 kias, the audio seemed a bit loud. Critical timing and communication happening RP in bound. When the cue happens, no other communication will be heard.”
- “The aural cueing was great during takeoff and landing, it gave me the callouts that I would want from either my crew chiefs or co-pilot. During the enroute phase it was less useful as it mainly called out speed changes. I felt these callouts were slightly jarring and didn't really require the computer lady to scream it in my ear. I'm unsure if it was actually louder than during takeoff and landing, but it seemed that way due to the longer periods of silence during the enroute phase.”
- “The aural cueing is very useful in alerting me to route and speed changes, as those are things that can be easily overlooked by a pilot during similar situations. I only ever heard altitude callouts on climb out on the first takeoff of each session with the exception of one takeoff where the subsequent point had been cycled forward and back a few times.”
- “Good helpful.”
- “When it was working it was great.”
- “Very loud and irritating at times, a smoother, more pleasant voice would be more appropriate especially when listening to someone over headset.”
- “Still somewhat loud and obnoxious… Fairly decent on approach and hover to provide height cues.”

Comments related to tactile cueing include:

- “My least favorite cueing of the system. As I'm taking off, I don't need the belt vibration reminding me I'm slow. I know I'm slow, I just took off, or….I may have had an H-Hour change, and I deliberately changed my speed. The corridor is pretty narrow, and if you overshoot it, you'll get buzzed. I don't need to be buzzed when I'm in the enroute mode.”
- “Still my least favorite feature, and unneeded.”
- “The tactile cueing felt relevant without being overwhelmed w/ information.”
- “Did not feel excessive or overdone. Did not consider a distraction.”
- “Easy to interpret, easy to use. Very good.”
- “This is likely the hallmark feature of the entire system. I would keep this in its current form.”
- “The tactile cueing provided a for a faster control input when a drift occurred and was surprisingly easy to process.”
- “Very good cueing and easy to determine required input. Only issue was when I first started the session the belt was upside down on the seat and when I put it on that way left

and right cues would have been mistaken. I only recognized it after I put the lap belt on when I looked down and saw the insignia upside down.”

- “The tactile cueing was very useful during all modes of flight and allowed me to quickly identify the parameter that needed fixing. During a hover, I feel like I may have been able to better hold my position if it were more sensitive, alerting me of drift at an earlier time.”
- “The tactile system is very useful. I would want a bit more sensitivity during a hover. I find it easier to correct small mistakes as opposed to fixing my drift after 10 feet.”
- “Good.”
- “Tactile cueing was good but I mentioned that it needs to be added to the enroute phase if using set B symbology.”
- “Almost just as pointless as the aural cueing… Whereas it helps to know where you are drifting, especially in a hover, most pilots can see that they are drifting and attempting to correct. This just gives one more input to the body to take into account and may cause distraction. It did make me jump once or twice because I was not expecting it.”
- “Got more used to using this system and started to respond to it when cues were provided to speed up or slow down.”

Comments related to controllability of the aircraft include:

- “Well, I don't fly the simulator particularly well to begin with. Then putting this system on provided some frustrating challenges, but at the last iteration, I was able to confidently control the aircraft. I would like to fly this system in an actual aircraft.”
- “Once I was comfortable with the symbology, control of the aircraft was normal for a simulator.”
- “Flew like an ordinary aircraft in the simulator.”
- “Simulator never performs as well as aircraft, however; I could never figure out the system behind the approach once the speed started coming down. It would always get away from me in one aspect or another. Much easier with the collective coupling - I think that would be a must if this system were to go to market. More predictability in the approach would be appreciated.”
- “Understanding that the simulator is inherently more difficult to control especially while performing VMC flight maneuvers, I think that aircraft control is easier with the helmet mounted display rather than the PMD. The peripheral cues that your eyes pick up even in the weather make using the PMD alone difficult to use. I would only want to use the PMD in a fully coupled mode, while I would feel comfortable hand flying while using the HMD.”
- “Simulator yaw trim system seemed to be off. More left pedal pressure was required during approach phase (picture on screen required pedal input with little change to trim ball on mfd.”

- “Once airborne, the aircraft handled much like I would expect a real aircraft to. I had issues during takeoff and during the final phase of landing, but I believe that was due to the simulator as opposed to any of the cueing systems.”
- “As I became more accustomed to the system, my controllability increased. I believe if I were able to see the rotor system, I would have much cleaner takeoffs.”
- “It’s a sim. Not always what it really does. Pitch change for no reason and trim is not responsive like the AC”
- “Only issues were drift on takeoff when using the PMD or the HMD. Attitude is not the same as displayed by the Attitude indicator.”
- “This, much like any other H-60 Simulator is extremely difficult to control, at first. Once used to it, it becomes much easier, however, it has its quirks that make things that much more difficult. Such as: Cyclic moves back to position even though moved with trim released causing the aircraft to move back in the opposite direction. Pedals are very sensitive. I found it much easier near the end to almost not use them at all unless I had to, because doing so would cause such drastic yawing that it would make it extremely difficult to re-orient to a maneuverable attitude.”
- “Much easier to control with the A symbology!! Because it was more accurate in its placement of where it wanted the controls, there was not thought into what was needed to make the A/C do what you wanted. Had some difficulty at times maintaining trim for whatever reason the aircraft would suddenly lunge out of trim with no control inputs. Also had minor difficulties at times during takeoff, but once the cues were followed, it was easy.”

Comments related to helmet mounted display (HMD) hardware include:

- “Seemed fine.”
- “The image was reasonably clear. Came through better under visibility below 1 mile.”
- “Needs a counterweight in the back like a set of goggles. Otherwise, really nice.”
- “If the hardware were able to be fitted comfortably, probably with the use of a counterweight, this would be the optimum system for me. The system in its current form was incredibly uncomfortable, but I am attributing most of the discomfort to the eye tracking glasses and the electrodes on my scalp buried under a helmet that was the wrong size and not fitted to my head.”
- “The HMD was very uncomfortable when couple with head harness and eye tracking device.”
- “Overall the HMD was useful in its presentation and the information available. In both instances it caused a great strain on my eyes that caused a headache and eventually slight nausea. The second iteration was less painful than the first. I was also having issues getting the entire display in perfect focus. I could only get either the top or the bottom sections in perfect focus with the opposite being out of focus, but still readable. It was manageable by focusing the middle section and having both the top and bottom ever so

slightly out of focus. Interestingly, however, even when the heading and torque were slightly out of focus, the nav stack in the upper right was still clear."

- "The helmet mounted display hardware was much easier to use as I became accustomed to it."
- "Nice."
- "It was good."
- "Great tool for situational awareness. There were hot spots around my ears when wearing the eye tracking glasses and the helmet."
- "Not horrible. Somewhat difficult to get use-to. Once on, I felt as if my head was very restricted on movement, and therefore tried not to move so much but focus on what was in front of me. Adjustments were not difficult to figure out, much like ANVIS."
- "Was irritating at times especially with the EEG and the visual sensor glasses… also had difficulty with moving my head around. I rarely moved my head because of the restriction I felt it was given. HMD also seemed to not give the flull left, or up sight picture. I am unsure if this was its position on my head or the interference of the EEG and glasses."

Other comments include:

- "A set symbology, after training, appeared to be more effective than B at bringing a pilot to a point on the ground or in space with the very precise guidance offered."
- "I think that in order to get the best and most honest results with the HMD, aviators should be able to drop their own personal helmet off to be retrofitted with the HMD hardware before the study. The HMD is far superior in terms of situational awareness and aircraft controllability, but it probably gets a bad reputation because it is so dang uncomfortable to wear with all of the other research equipment."
- "Total system still needs re-fining (I feel) but is an amazing product thus far which could really aid pilots in a DVE."
- "Overall very easy to use and learn. Intuitive only because (I feel) I am already a pilot. Not too cluttered, but also I had a tendency to focus only on symbology alone, and no other input. Good and bad, I believe."

Appendix M. Trust in Automation Comments

Trust in Automation Questionnaire Comments include:

- "The collective coupling capabilities are impressive. After seeing it operate a few times it allowed me to trust the system more and focus my attention on the other aspects of the approach."
- "Additional iterations only continue to increase my confidence in the system as I become more familiar with the indications."
- "I know what the system is going to do enroute but am not wholly confident it will aid in avoiding collision with terrain (vertical deviation bar). I'm not too trusting in the coupled collective to the ground because of when it decides to take me to the ground. It might bring me down while I have lateral movement, which is a no-go for me. I found myself overriding the system during the final 5 feet to ensure I touched down with either forward or no movement."
- "I am a little unsure about the system's collective inputs near the ground and find myself overriding the control to ensure that I touchdown with either forward or no drift, as opposed to lateral or rearward drift."
- "If I am unable to visualize the upcoming terrain, I cannot anticipate when the route climbs and descends. As for the route indication on the ground, there were times that I lost it behind undulating terrain and another time where I could see it despite the terrain and could even tell what the terrain was doing ahead of me."
- "I have a hard time understanding what the aircraft cue is doing on the approach. Also symbology gets confusing."
- "I can see how this could really help."
- "The system seems to make the correct inputs to the collective while it is coupled. Seeing it work during various weight configurations was reassuring that it works."
- "The systems work as advertised. I am having a hard time applying the data while flying the sim. This is especially the case on takeoff and hovering."
- "Pilots will need extensive training of the system in order to properly, and safely use it. This may look like the training AH-64 pilots get with their use of their systems while flying the bag."
- "The system behavior does not directly translate to the attitude indications provided by the traditional instruments."
- "Perhaps more realistic indications would allow pilots to have more trust in the flight control guidance."
- "I believe with more time, utilizing and training to proficiency, I could much more easily manipulate and control the aircraft with the provided cueing, yet the symbols are not necessarily immediately intuitive."

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