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Techniques to Explore Spatial Audio Cues for Aiding Helicopter Navigation in Degraded Visual Environments

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14. ABSTRACT

Aviation mishaps resulting from degraded visual environments (DVEs) cause a significant loss in military personnel and aircraft every year. DVEs are considered to be any type of environmental condition (e.g., fog, blowing sand or snow) that reduces visibility and can cause the loss of spatial orientation. For helicopters, DVEs are often created by the aircraft rotor downwash recirculating sand or snow while hovering or during landings. This report describes new techniques for testing and validating sensory cueing displays to aid helicopter flight in DVEs. Research through a tri-service effort will be using the approaches reported here to investigate the advantages of utilizing spatialized auditory cues for locating and tracking objects outside the aircraft during simulated helicopter flight when there is an obstructed field of view. Application of these techniques will provide critical proof-of-concept information on sensory cueing displays for helicopter flight in DVEs.

15. SUBJECT TERMS

auditory localization, aviation, sensory cueing, spatial orientation

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Summary

Background

Pilots often need to fly in degraded visual environments (DVEs), which are any type of environmental condition that visually obstructs the pilot's view of outside the aircraft (e.g., low illumination, fog, etc.). For helicopters, DVEs can also be created by the aircraft rotor downwash recirculating loose terrain during landings or while hovering above a particular location. These situations are known as "brownout" or "whiteout" conditions, and occur when above sandy or snowy areas, respectively. As one might imagine, navigating a helicopter through DVE conditions such as these is an extremely challenging, stressful, and inherently dangerous task for pilots. This is because the loss of visibility can lead to spatial disorientation, which refers a pilot's inability to correctly interpret the aircraft's relation to the ground or other points of reference. Aviation mishaps resulting from DVEs represent a significant loss in personnel and aircraft every year. As such, there is a major focus on researching technologies that prevent mishaps in DVEs by enabling a pilot to better maneuver and maintain spatial orientation when he or she loses visibility of what's outside the aircraft.

Purpose

The current project represents a collaborative tri-service effort aimed at spatial audio cueing as a potential solution for helping pilots fly, maneuver and navigate in DVE conditions.

Methods

Directional cueing (i.e., indicating the location of target waypoints) was achieved by spatializing an auditory stimulus using the SoundLab audio rendering package and convolving audio signals with (non-individualized) head-related transfer functions. Two spatial cue conditions were tested, either rendered dynamically in reference to the pilot's head via head tracking or with respect to aircraft heading. Data were collected from pilots operating a full-motion UH-60 Black Hawk flight simulator at the U.S. Army Aeromedical Research Laboratory (USAARL) at Fort Rucker, AL. Pilots performed multiple flight maneuvers for localization tasks such as "turn to target", "side step to hover", and "approach to moving target." Performance was assessed by measures of localization error, completion time and failure rate.

Conclusions

Providing pilots with three-dimensional (3D) audio cues allowed them to find targets outside their field of vision and in DVEs quicker than when they didn't have the cues. When given 3D audio cues, pilots were able to fly to a moving target in DVE, which they would not be able to do otherwise. Findings from this study provide information on sensory cueing display countermeasures for helicopter flight in DVEs.

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Acknowledgments

This research effort is supported by the Joint Program Committee (JPC-5) for Aviation Mishap Prevention and the Military Operational Medicine Research Program. We would like to thank Rolf Beutler for all his time, effort, and help with designing and coding feasible scenarios in the NUH-60 Flight Simulator. We would also like to thank the Flight Systems Branch at USAARL for their help with facilitating the use of the flight simulator and assistance in creating the scenarios. We would like to also thank the Warfighter Performance Group and the USAARL Commander for their support during the development and execution of the planned study discussed here.

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Table of Contents

List of Figures

List of Tables

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Introduction

Navigating aircraft through environmental conditions that limit visibility (e.g., fog or rain) is a challenging and potentially dangerous task for aviators. Any type of environmental condition that obstructs the pilot's view is known as a degraded visual environment (DVE), and is inherently hazardous since vision is believed to be the only reliable sensory cue used for orientation in flight (Colucci, 2007; Vidulich, Wickens, Tsang, & Flach, 2010). Aviation mishaps resulting from DVEs have been reported to cost over $100 million per year (Albery, 2012; Whittle, 2012). As such, the U.S. military services are focused on researching mitigation techniques involving training and/or devices to prevent mishaps in DVE conditions. Research at the U.S. Army Aeromedical Research Laboratory (USAARL) at Fort Rucker, AL, in collaboration with the Air Force Research Laboratory (AFRL) 711th Human Performance Wing and the Naval Aerospace Medical Research Unit – Dayton (NAMRU-D) at Wright-Patterson Air Force Base, is investigating augmenting sensory cueing as a potential solution for enhancing pilot performance in DVE conditions. Here we discuss the use of veridical earth-referenced spatial, or three-dimensional (3D), audio cues for aiding guidance to a target location and tracking objects around the aircraft during flight in DVE conditions.

Helicopter Flight Challenges in DVE Conditions

Common causes of DVEs include fog/clouds, night, and precipitation. For rotary-wing aircraft, DVEs are also created by the rotor blades blowing up sand or snow as the helicopter approaches the ground. These conditions are known as "brownouts" or "whiteouts" depending on the obscurant. Helicopter landings in DVEs have been reported as the overall largest cause of rotary-wing airframe loss in the U.S. services (Albery, 2012; Colucci, 2007). During an approach and landing in a normal visual environment, pilots often rely on outside visual references to estimate the aircraft's position, altitude, and motion relative to the ground and surrounding structures. Once the pilot enters a DVE, these outside visual cues deteriorate. Switching to flight instruments does not solve the problem entirely, because the instruments may not provide enough information about key parameters (e.g., aircraft descent rate, ground speed, drift, height above terrain, terrain features, landing point location, obstacle clearance) quickly and intuitively enough to maneuver and/or land safely. Thus, a DVE increases the pilot's risk of crashing due to excessive descent rates, unintended drift (which can cause rollover upon landing), and collision with ground obstacles.

The increased risk of flying in DVEs is not limited to military aviation, since civilian helicopters also operate in DVEs. Search and rescue operations and air ambulance flights are often dispatched in bad weather with poor visibility. In fact, DVEs may actually increase the demand signal to launch medical evacuation (MEDEVAC) flights. An example would be an air ambulance mission in response to an auto accident caused by poor visibility conditions, thereby drawing the helicopter pilot into a DVE. Thus, any solutions found for military operations in DVE would potentially have direct benefit for civilian operations.

For a pilot to successfully execute maneuvers in such conditions, information from the environment must be obtained by the aircraft systems (e.g., location points for landing, any terrain that may interfere with a direct course) and delivered to the pilots in a meaningful way

(Albery, 2012). One promising technique is to provide pilots with accurate information about the environment around the aircraft using spatial sensory cues that are inherently intuitive as opposed to information provided through multiple sensory inputs. Several approaches have been developed to assist an aviator navigate through a DVE and many of these aides involve visual displays and/or modifications of symbology presented to the pilots. However, there is evidence to suggest that this type of heavy reliance on one type of navigational aid can lead to errors in flight due to the high mental task load (Ward & Scholl, 2015). Recently, Russell and colleagues (2016) evaluated existing visual symbology sets, haptic cues, and aural prompting for their compatibility, benefit, or conflict when used simultaneously in DVE. In general, the results indicated that test pilot flight performance improved when using advanced visual symbologies, particularly when combined with supplemental aural and/or tactile cueing (Russell et al., 2016). The audio-specific techniques reported here were developed to specifically investigate the potential benefits of including spatialized audio cueing during simulated helicopter flight in a DVE condition.

Spatial Audio Cueing

Generally, auditory cueing is defined as any acoustic indicator of environmental and/or situational information relayed to an individual (Begault, 1993; Dehais et al., 2014; MacIsaac, Stiles, & Judge, 2005; Russell et al., 2016). In flight, pilots can receive flight parameter and environmental variables, such as aircraft attitude, altitude, and terrain/object collision warnings. Such audio cues are typically delivered through over-the-ear headsets or insert ear pieces such as the Communications Earplug (CEP). Although auditory displays are incorporated into many operational interfaces, they are typically rudimentary in functionality and provide partial, if any, guidance that includes the natural spatial auditory information available in a natural setting (Simpson et al., 2005; Simpson, Brungart, Dallman, Yasky, & Romigh, 2008). Spatial auditory display technologies (i.e., 3D audio displays) may fill this gap by exploiting the properties of the binaural auditory processing system. Such displays seek to provide the intuitive spatial information to an operator that would naturally be available and thereby aid the operator in determining the location of a sound source more rapidly and accurately (Simpson et al., 2007; Simpson et al., 2004; Simpson, Brungart, Gilkey, & McKinley, 2005). These technologies could help improve pilot safety and performance by indicating the direction of an object located outside the field of view or obscured by a DVE (Veltman, Oving, & Bronkhorst, 2004), potentially reducing the sensory load and mental workload of the pilot.

Spatial audio technology creates the perception that sounds are outside of the head (often referred to as externalization) by introducing differences into the sound presented to the two ears (Wenzel, Miller, & Abel, 2000). More specifically, sounds are altered by introducing information contained in the head-related transfer function (HRTF), which introduces differences in the arrival time (as much as 700 μsec) and level (as much as 40 dB) at the two ears, as well as spatially-dependent spectral filtering based on the external ear shape. These signal processing techniques used to "externalize" an acoustic signal have a long history of use in auditory research, and many compelling demonstrations are readily available on the internet. It is extremely important to note that the delivery of spatial audio *requires* stereo audio connections and headset. Their use in aviation for cueing pilots has been in consideration for over two decades: for example, the U.S. Marines flight tested 3D audio displays, developed by the U.S.

Air Force's Armstrong Laboratory, and demonstrated that targets could be localized to within 10 degrees using this technique (Williamson, 1990).

Experimental Setup

The current study was conducted under the supervision of the U.S. Army Aeromedical Research Laboratory (USAARL) Regulatory Compliance Office and the U.S. Army Medical Research and Materiel Command Institutional Review Board. Study participants were military trained aviators recruited from in and around Fort Rucker, AL, that were self-screened for current active flight status, over 200 hours flight time, normal hearing and normal or corrected to normal vision. Participants reviewed and signed an informed-consent prior to enrollment in the study, and were compensated for their participation (if participating in an "off-duty" status).

Study Objective

The flight test measures include quantitative assessment of speed and accuracy of flight performance along the dimensions described below. Speed rather than accuracy is the variable that tends to change under perturbation when subjects are proficient at a task, as would be the case with our aviator subjects5. While speed of performance is not the sole measure in this study, it is a relevant variable and one that will be comparable and standardized across all tasks and conditions, so it is a convenient and relevant case for discussion. Consider a hypothetical case where a 120-second flight (i.e., one monolithic meta-task in order to make the discussion tractable) can be done at least 10 seconds faster with better cueing (which would be relevant to our main hypothesis). This amount of change was deemed to be operationally meaningful in military situations, such as exposure to enemy fire while unloading Soldiers or completing a medevac mission, wherein a savings of 10 seconds would be most welcomed to the pilot and crew.

NUH-60FS Flight Simulator

One of the assets at USAARL is an NUH-60FS Aeromedical Research Black Hawk Flight Simulator. The NUH-60FS (Figure 1) is fully accredited by Directorate of Simulations (DoS) and Program Executive Office Simulations, Training, and Instrumentation (PEOSTRI) as a 6-degree of freedom, full-motion, and full-visual (Level D equivalency) Black Hawk helicopter flight simulator. It has unique features optimally designed for testing and aeromedical research. The instrumentation panel of the NUH-60FS can be configured to replicate the Alpha, Lima, or Mike model Black Hawk. Other capabilities include: an environmental control system for cockpit climate (i.e., temperature) control, sound and noise replication, infrared sensor emulation with advanced flight symbology, and 7 Dell XIG Image Generators. The immersive, enhanced brownout dust modeling and environmental simulation models make the NUH-60FS an ideal test platform for studying the effects of altered visual and audio cueing on pilot performance during DVE while in a safe environment. The image generators can simulate natural helicopter environment surroundings for: day, dusk, night, dust, snow, rain, clouds, use of night vision goggles (NVG), and infrared scenarios.

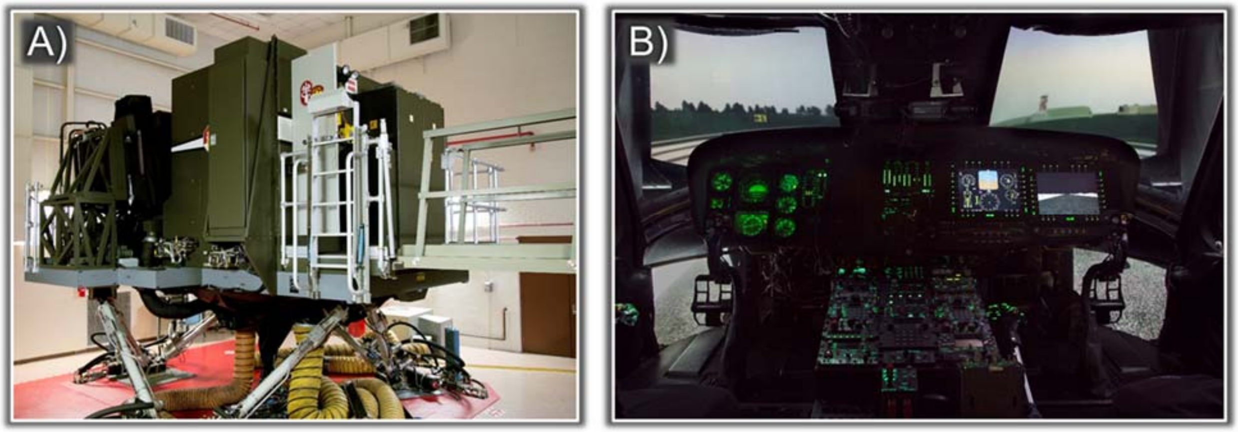

Figure 1. Research Platform. A) NUH-60FS full motion Black Hawk flight simulator. B) Cockpit view from inside the flight simulator.

Experimental Procedures

A 3D audio display for navigation was evaluated with three flight tasks that are based on tasks from the Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military Rotorcraft (ADS-33E-PRF) (United States Army Aviation and Missile Command, 2000). The experimental design entails a repeated-measures study with four order-balanced conditions:

(Control) No DVE (complete visibility)
(A) DVE + no auditory cueing,
(B) DVE + head-referenced (H/R) auditory cueing,
(C) DVE + aircraft-referenced (A/C) auditory cueing.

Flight performance variables described later in more detail were the main dependent measures (see Flight Maneuvers and Flight Performance Metrics). Table 1 lists the flight tasks.

Table 1. Flight Maneuvers Tested

Flight Tasks	Aircraft Position	Cueing Direction
1. Turn to Target	Fixed	Varying
2. Sidestep to a Hover	Varying	Fixed
3. Approach to Moving Station	Varying	Varying

Flight Maneuvers and Flight Performance Metrics

1) Turn to an unknown object

From a fixed-hover (Figure 2), the pilot will use the anti-torque pedals to change the aircraft's heading (yaw) to the left or right while following spatial audio directional cues that will facilitate visual localization, identification and tracking of an unknown object initially outside of the pilot's visual field. The maneuver will stop when the pilot locates the object, which will be a vehicle facing the aircraft, and points the aircraft nose directly at the vehicle (see Figure 2). Performance metrics for this maneuver include localization/alignment error, fail rate, and time to complete the task. The goal is to determine whether pilots can locate a target in DVE from a fixed-location using only spatial audio cueing as well as whether spatial audio cues improve a pilot's ability to locate a target with no DVE.

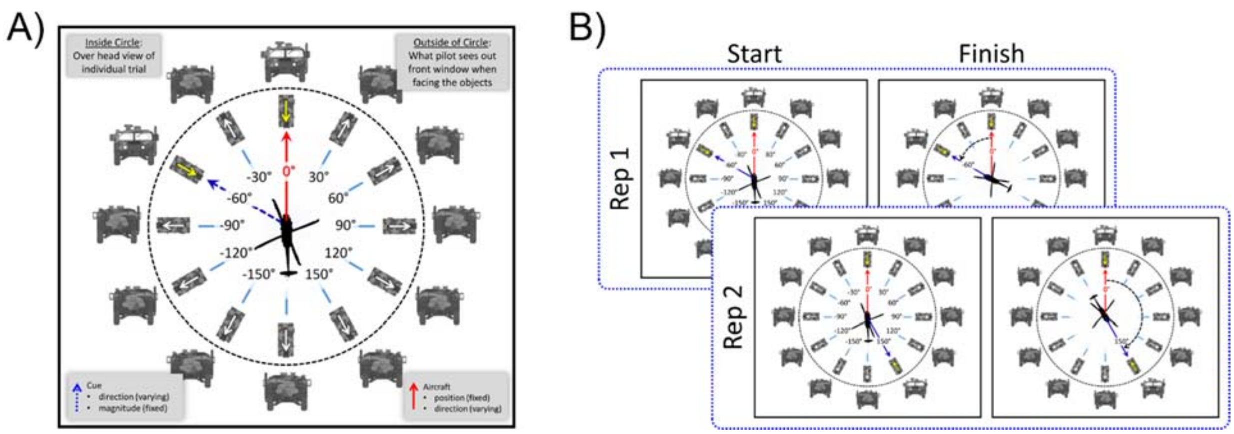

Figure 2. Turn to target task. A) An overhead view of the aircraft is represented inside the dotted circle in reference to its position to locations. The trial starts with the aircraft pointing forward at a vehicle facing the pilot. The task is then to find the other vehicle facing them and point the aircraft at it. B) Schematic of individual trials.

2) <u>Sidestep to hover</u>

Using a "sidestep maneuver" (Figure 3A), the pilot rapidly relocates the aircraft from a hover to another target location, directly over the vehicle facing the aircraft (Figure 3B). The vehicle appears at randomly pre-designated angles (±30° and ±90°) and distances (35, 40, and 50 feet). The pilot applies necessary control inputs to prevent unintended drift or heading changes. Performance metrics for this maneuver include time to completion, maximum lateral velocity, altitude maintenance, heading maintenance, relocation accuracy, deviations from an ideal sidestep path (forward/aft drift), and 20 seconds pre- and post-hover quality (heading, altitude, and position). The goal of this task is to determine if pilots can move toward and hover above a target in DVE using spatial audio cues and whether spatial audio cues improve a pilot's ability to move toward a target and hover above with no DVE. Pilots were instructed to respond when they had eyes on target through their chin bubble, because they are not able to know when the vehicle would be directly below the aircraft.

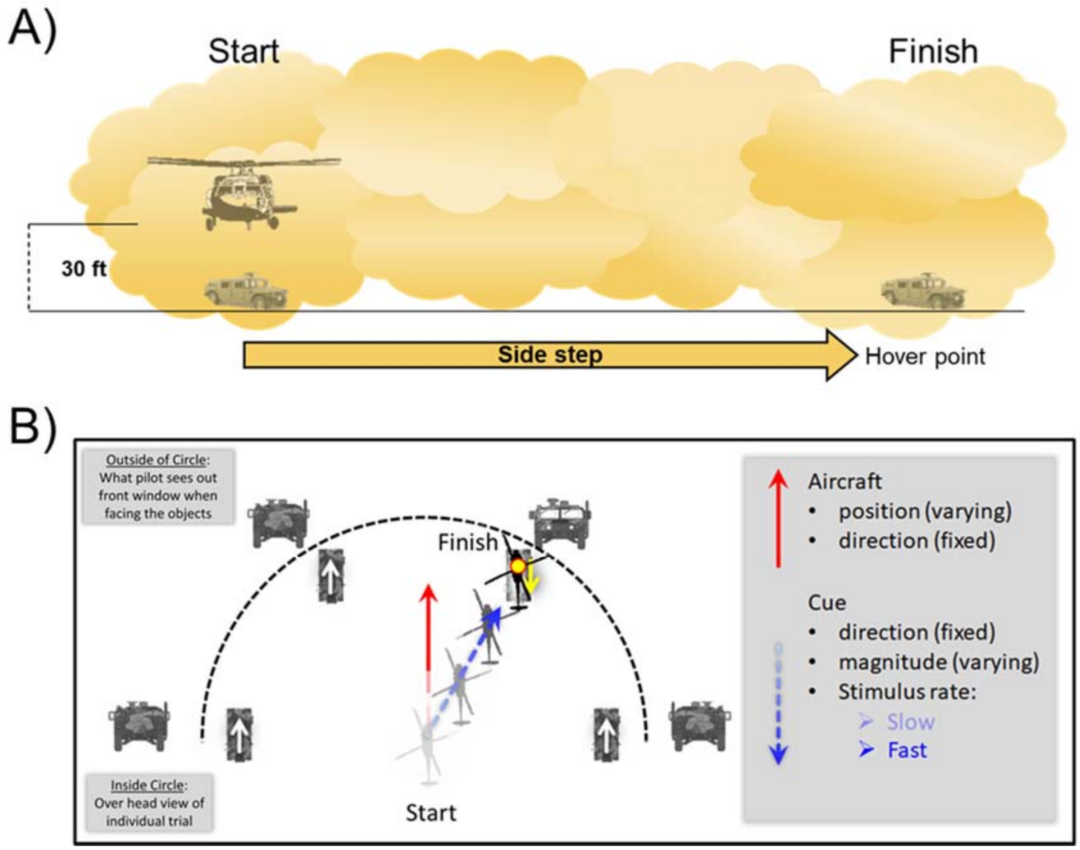

Figure 3. Sidestep to hover task. A) Schematic showing the sidestep-to-hover maneuver. B) An overhead view of the aircraft is represented inside the dotted circle in reference to its position to locations. The trial starts with the aircraft pointing forward at a vehicle facing the pilot. The task is then to locate the other vehicle facing them and sidestep the aircraft to a hover over the target location.

3) <u>Approach to station keeping over a moving object</u>

This task starts with the aircraft 250 ft above ground level (AGL) moving at 80 knots toward the landing point on a Navy vessel, 1.5 nautical miles (nm) away (see Figure 4). Descent from 250 ft. AGL will start at 0.8 nm from the planned hover point above the ship. The pilots are to approach the landing point in a straight line, and approach to a hover over the landing point of the ship. Forward motion will be as required to maintain station keeping over the intended hover point, taking into account the ship’s movement. Candidate performance metrics for this task include time to completion, and deviations from: ideal approach path, intended hover point, hover heading, and hover height. Crashes, loss of control, missed approaches, and/or aborted landings will also be recorded. The goal of this task is to determine if pilots can locate a target in DVE using only spatial audio cues, while changing both position and direction.

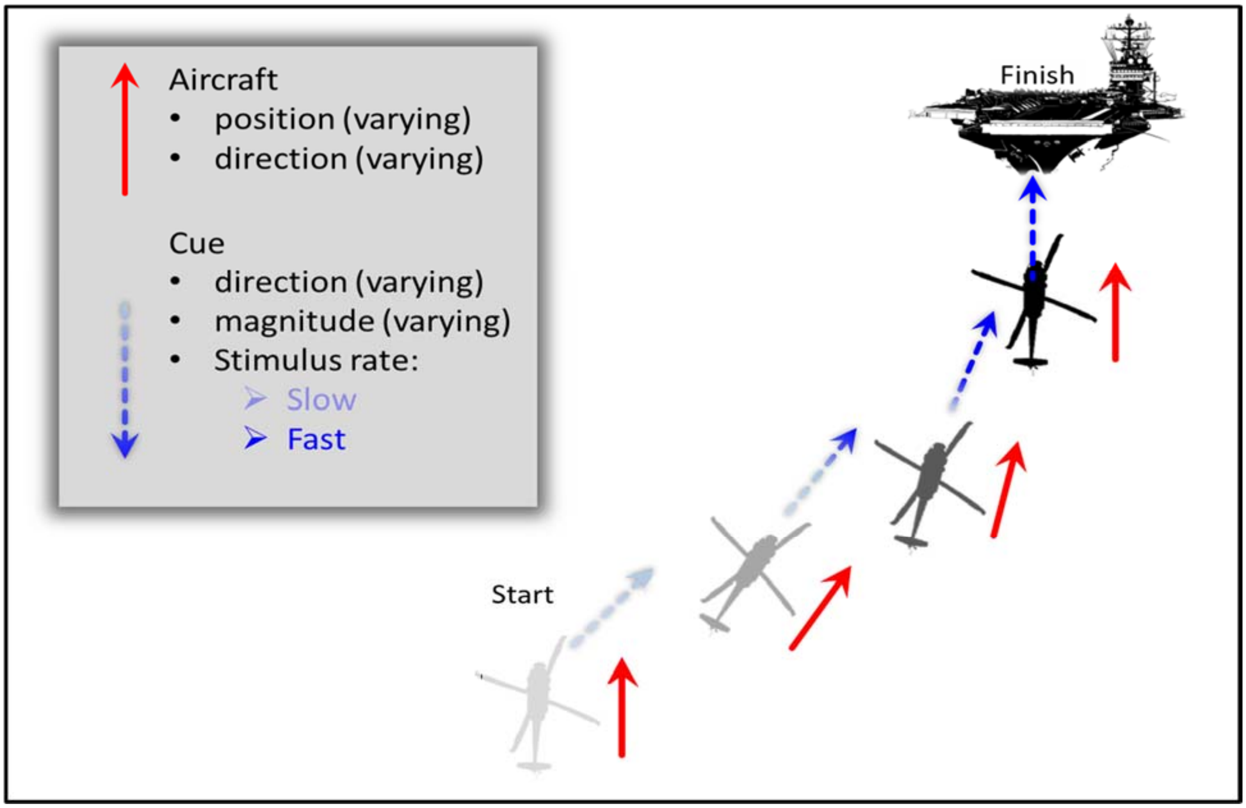

Figure 4. Approach to moving station task. The trial started with the aircraft at a fixed distance away from the aircraft.

Experimental Conditions

Data collection was separated into testing blocks representing one of the four cue conditions. For each block, three sets of trials were collected for each maneuver and all the sets were completed for that condition before proceeding to the next condition. The order of the conditions was counter-balanced (see Table 2). For example, Subjects 1, 7, and 13 were tested in the following order: (CON) Control condition, (A) DVE + no cues, (B) DVE + H/R cues, and finally (C) DVE + A/C cues. The first condition block for all subjects was complete visibility, i.e., No DVE condition (see Figure 5 and 6, top images). This block served two purposes. First, it gave pilots a chance to become familiarized with the task and the simulator. Second, it served as a control condition in which the performance of the pilots using currently fielded technologies and high visibility could be measured and compared to the DVE conditions.

Table 2. Condition Block Ordering

				Subject #	Subject #	Subject #
CON	A	B	C	1	7	13
CON	A	C	B	2	8	14
CON	B	A	C	3	9	15
CON	B	C	A	4	10	16
CON	C	A	B	5	11	17
CON	C	B	A	6	12	18

DVE Simulations

The enhanced brownout dust model used in the NUH-60FS is capable of accurately simulating blowing and billowing dust. The simulator allows for the experimenter to control dust cloud parameters, such as: density, dust particle size (fine to heavy), and dust cloud height (0 to 100 ft AGL).

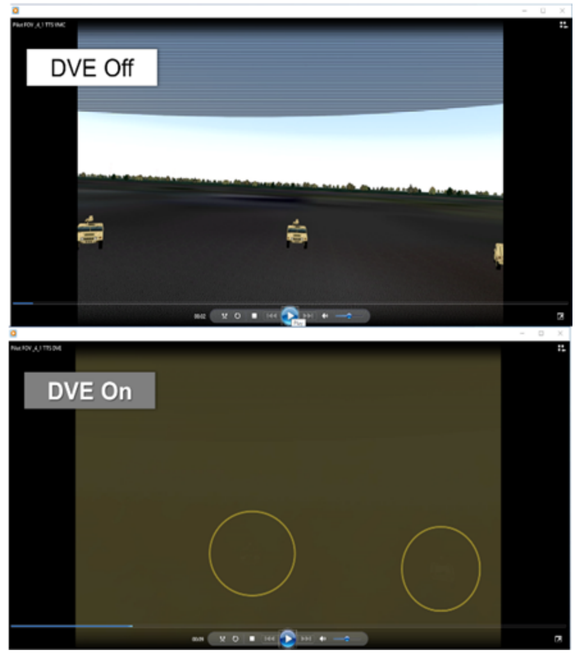

Figure 5. DVE simulation for turn to target and sidestep to hover maneuvers.

(Top) The field of view of the pilots for the turn to target task is shown. Each trial started pointing at a vehicle that was facing the aircraft directly in front at 12 o'clock. The target vehicle was indicated as a vehicle that was also facing the aircraft and can be seen to the left of the starting point.

(Bottom) The pilot's field of view when the DVE simulation was turned on. The circles indicate where the vehicles are located. Note that while the vehicles may be difficult to see in this image, the pilots were typically able to visualize them.

Such capabilities enable the precise experimental control over the degree of visual field degradation. As such, performance metrics on various flight maneuvers were able to be collected from pilots during simulated flight in brownout conditions. This permitted a controlled, safe, and specific test of whether sensory cueing can enable the pilot to do something that would be considered atypical based on aircraft capability and/or personal preference.

For the approach to station, DVE was simulated using poor weather condition in which there was 200 ft ceiling and ½-mile visibility (see Figure 6).

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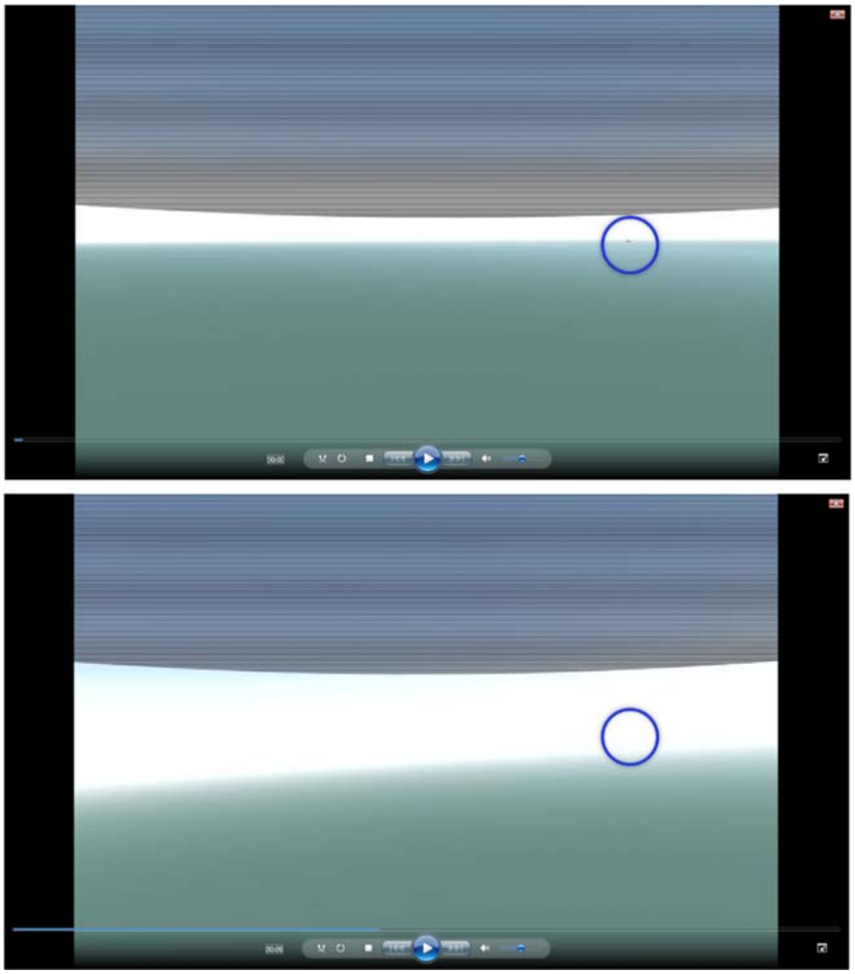


Figure 6. DVE Simulation for approach to moving station maneuver. (Top) The pilot's field of view under normal visibility conditions. (Bottom) The pilot's field of view when the DVE simulation was turned on. The circles indicate where the ship was located.

As can be seen in the blue circle of the top image, the moving ship is on the horizon. However, when the DVE simulation is turned on, the pilot loses complete visibility of the target ship. Because each trial started with the aircraft at the same distance and location away from the ship, 15-20 mph crosswinds were introduced and varied across each of the 3 approaches, either coming from the left, the right, or alternating between left and right. The pilot had no knowledge of the direction of the crosswinds. This was to ensure that the subject could not merely maintain a heading in the direction they believe the ship to be in order to find it.

Preliminary Results

The data collection procedures described above produce a large variety of datasets that must be analyzed and interpreted. Here, we show examples of the initial review of each data type to demonstrate the types of results and conclusions, as well as limitations, able to be drawn from this dataset.

Turn to Target (TTT): Spatial Audio Helps Pilots Locate Targets Quicker

Figure 7 shows a histogram of response times across all trials for the turn-to-target task. In general, there were more response times that were shorter in duration for both the spatial audio cueing conditions compared to both the "Control" and "DVE + no cue" conditions. One reason for this could be that in both the "Control" and "DVE + no cue" conditions, when the target was to one side outside of their field of view or behind them, the subject had a 50% chance of rotating in the correct direction. Turning the wrong direction increases the response time due to the fact that the aircraft has to transverse an additional distance around to reach the correct target location. However, for the two cueing conditions the pilot is provided information via the spatial audio cueing, which helps the pilot better discern whether to start turning left or right.

The number of incorrect turns were quantified and plotted (Figure 7, top right) and, as expected, the cueing conditions had a smaller percentage of responses in which the subject began turning the wrong direction. For the small percentage of times the subject turned in the wrong direction, these were instances when the target location was behind the aircraft; cues providing the information about left or right may be perceived as ambiguous.

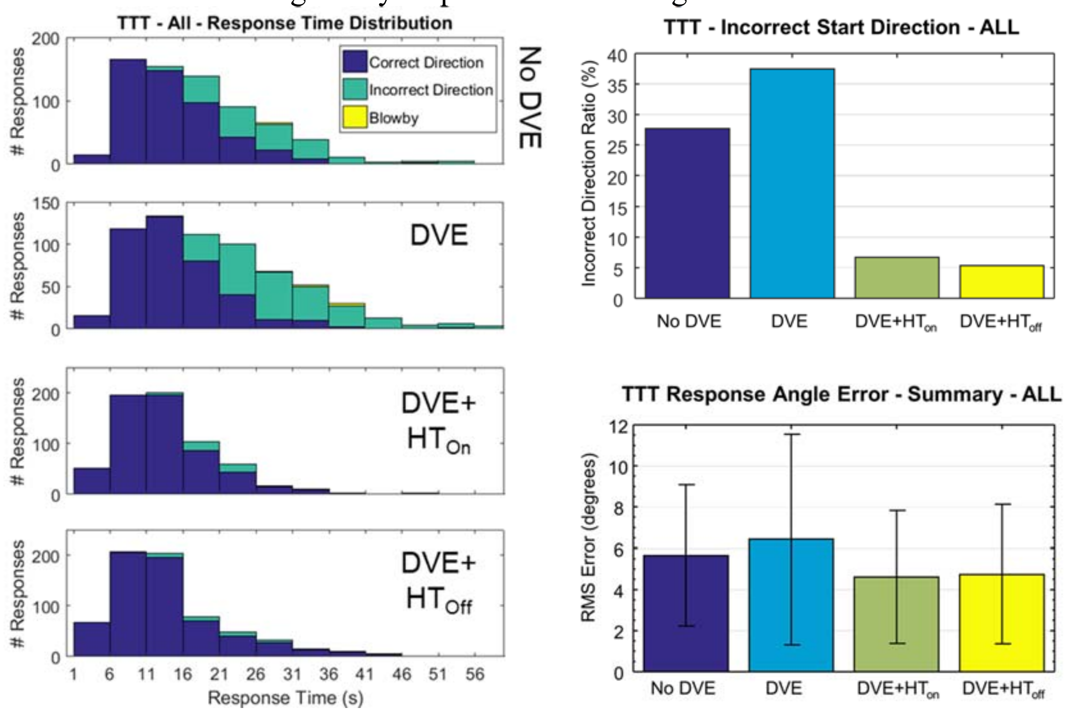


Figure 7. Turn to target response times and error measurements. (Left) The number of response bin by the response timer. (Top right) The percentage of incorrect or "turning away" from the target location. (Bottom right) The average and standard deviation localization error plotted for all subjects across all conditions.

Sidestep to Hover (SSH): DVE Degrades Maneuverability

Figure 8 displays the response areas for all subjects across all trials in the "Control" and "DVE + no cue" conditions. The target locations are indicated by the black and red dots on the figure (note since the target locations were the same for both conditions, the dots are overlaid). For the "Control" condition (light black ellipsoids), there is a tight grouping of responses as indicated by a smaller size in the response area represented. As expected, the pilots' performance became degraded in DVE conditions as indicated by the larger response areas (light red ellipsoids). Basically, the response locations (or the location the pilot indicated they were over the target vehicle) varied considerably between the "Control" and "DVE + no cue" condition.

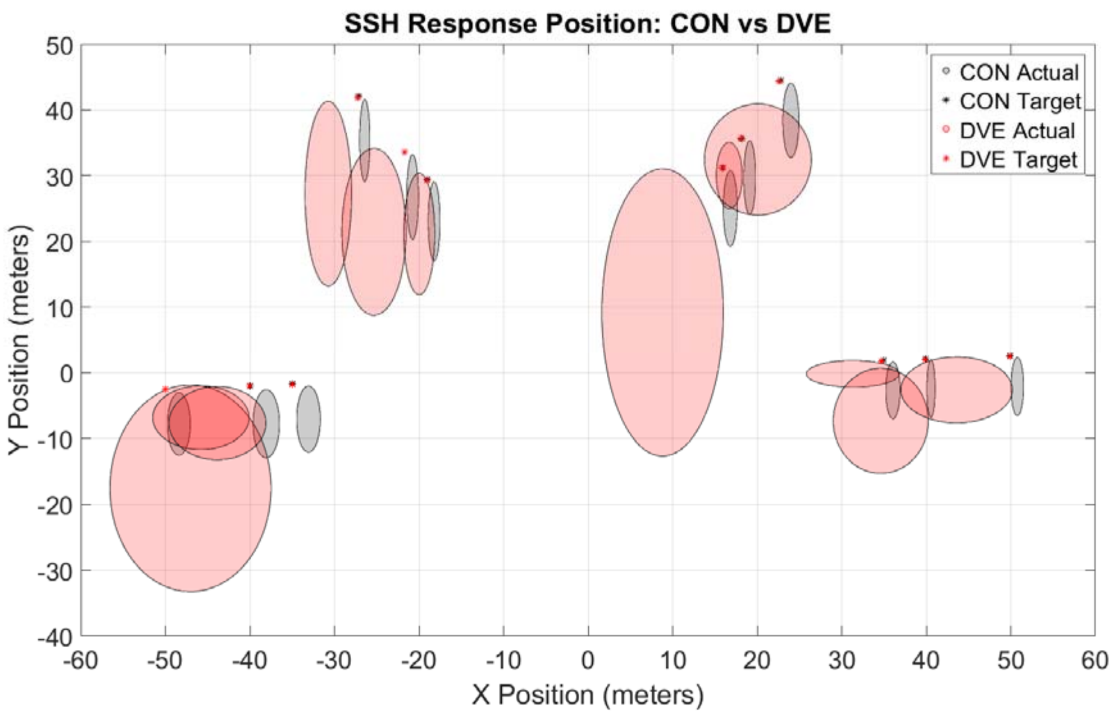
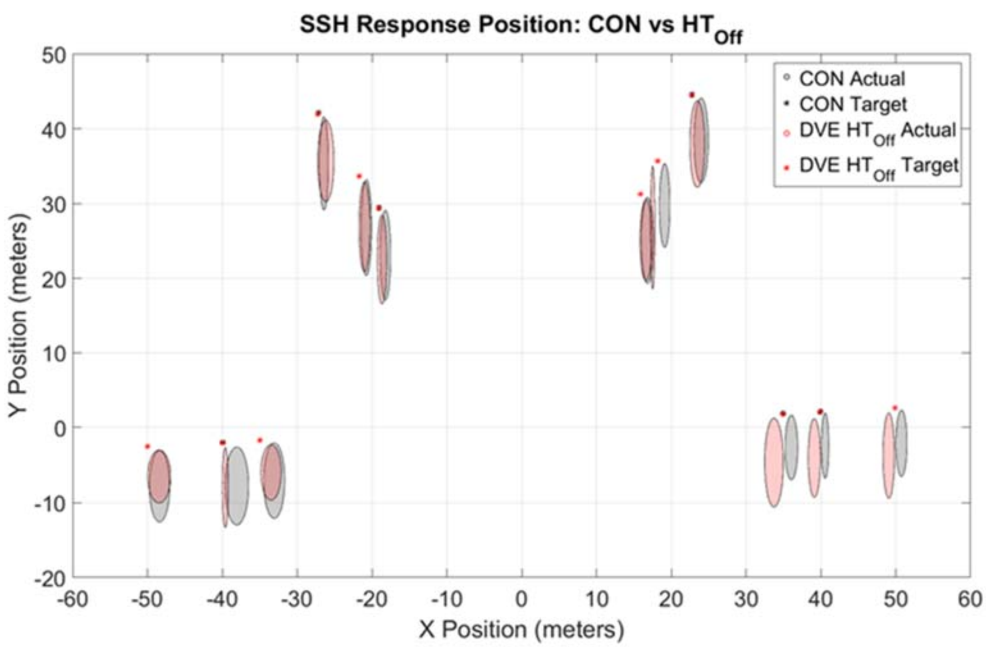


Figure 8. Sidestep to hover performance. The aircraft always started at location (0°, 0°) and then had to maneuver to the target location (i.e., the vehicle facing the aircraft) indicated by the small dots on the figure. The ellipsoid size indicates the spread of response locations across all trials and subjects.

Sidestep to hover (SSH): Auditory spatial cues improves maneuverability in DVE

Figure 9 displays the response areas for all subjects across all trials for the spatial conditions when head tracking was on (top) and off (bottom). It is important to note the pilots were visually handicapped by the simulated DVE in this task; however, performed comparable to the condition where they had complete visibility outside the aircraft. Qualitatively, it does not appear there was a difference between head or aircraft referenced for this task.

Figure 9. Spatial audio cueing performance on side step to hover task. As in Figure 8, the ellipsoid size indicates the spread of response location across all trials and subjects



(Top) Spatial audio was rendered according to head position relative to target location, a.k.a. head track ON. (Bottom) Spatial audio was rendered according to aircraft position relative to target location, a.k.a. head track OFF.

Approach to Moving Station (ATS): Pilots Completed the Task with Spatial Audio Cueing

Flight paths for each subject across all trials in the approach to station maneuver are plotted in Figure 10A. The color of the path indicates the cueing condition (note the DVE + no cue condition was tested for this maneuver). Figure 10B plots all the individual trails for four subjects. These plots are shown to illustrate a couple of points.

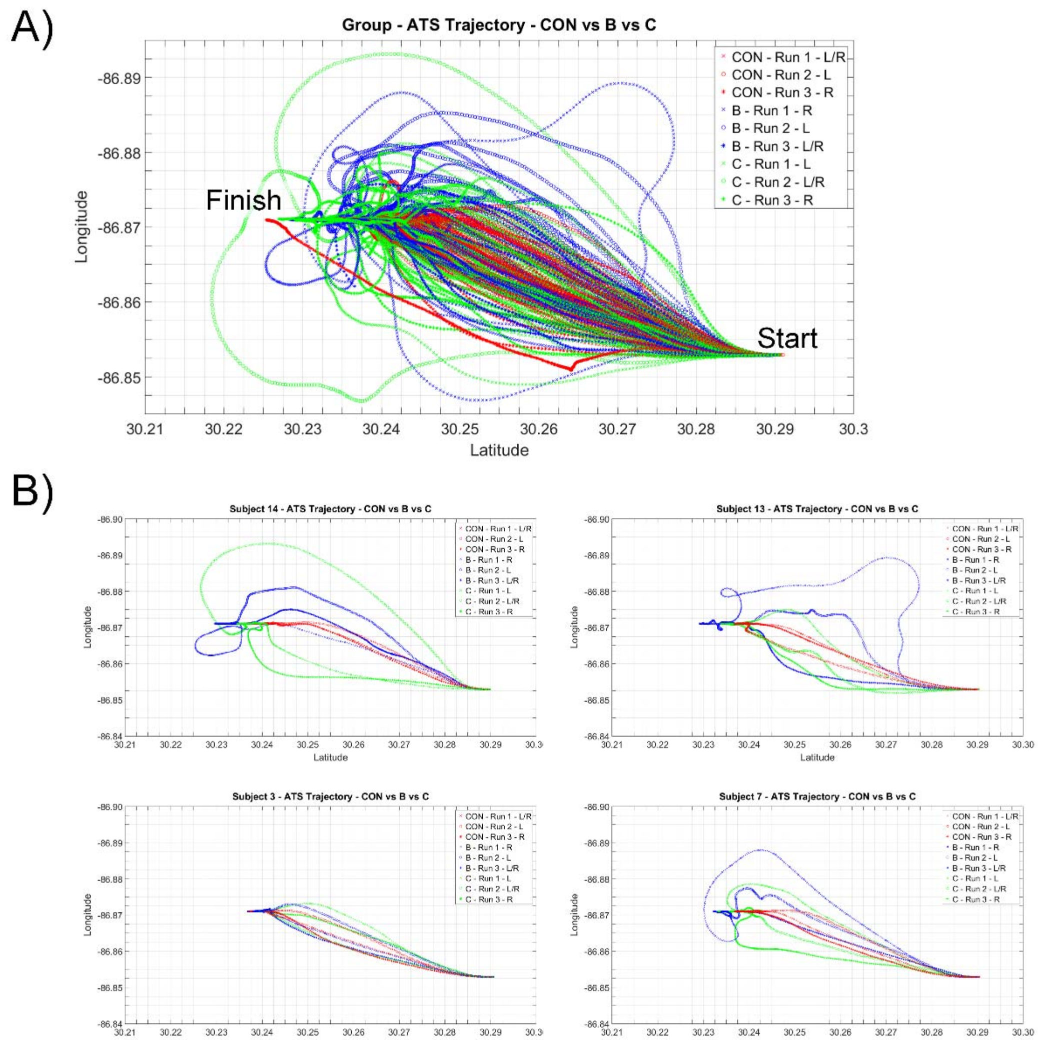


Figure 10. Approach to moving station flight trajectories. (A) The aircraft always started at a certain location and distance away from the ship. (B) All runs for all conditions for four individual subjects.

First, each of the subjects had no problem flying to the ship in the Control condition with complete visibility (red traces). Second, subjects were either able to use the spatial audio cues to help correct their flight trajectory if traveling in the wrong direction (Figure 10B, see blue trace in top right plot) or were able to perform comparable to their Control condition performance

(Figure 10B, bottom left plot). The most compelling finding from this particular flight task, was that the subjects were able to actively track a location and navigate in a difficult environment they wouldn't normally operate.

Conclusions

While sensory cueing has the potential to improve flight performance, it may also cause a type of sensory overload if an excessive amount of poorly coordinated cues (visual, audio, and tactile) are all presented at one time. One of the biggest questions remaining for a multi-sensory cueing approach is whether providing concordant sensory cues in combination can increase pilot flight performance. Following the completion of this spatial audio "proof-of-concept" project at USAARL, the next line of effort will be to address questions regarding the optimization of sensory cueing configurations across different modalities, the effects of sensory overload on pilot cognitive effort, and issues such as pilot trust in these sensory cueing systems during flight.

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