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# Audiotactile Aids for Improving Pilot Situation Awareness

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Up to one-third of all aircraft mishaps are attributable to spatial disorientation (SD), costing lives and millions of dollars. One potential solution is to provide supplementary sensory cues to help improve pilots' situation awareness (SA). Given existing demands on the pilot's visual system, audition and touch present the greatest potential for success. However, accurate 3D audio perception may be problematic in noisy operational environments. To determine the effects, participants performed an azimuth cue localization task while listening to 90 dB helicopter noise. Cue modalities conditions included 3D audio, vibrotactile, and audiotactile. Accuracy was better and response times were significantly faster for tactile and audiotactile cues than for 3D audio cues alone. The results illustrate the deleterious effects of loud ambient noise on 3D audio localization and suggest audiotactile cues may offer a viable alternative non-visual display for counteracting SD.

The aviation environment poses numerous challenges for maintaining situation awareness, including spatial disorientation (SD). Up to one-third of all aircraft mishaps are attributable to SD (Gibb, Ercoline, & Scharff, 2011), costing lives and millions of dollars. One potential solution to the SD problem is to provide supplementary sensory cues to help improve a pilot's situation awareness. Given a pilot's vision is already taxed through scanning numerous displays, we sought to use non-visual cues for communicating information without increasing the burden on the information-saturated visual channel. The primary goal of the present investigation was to evaluate the effectiveness of non-visual directional cues for improving situation awareness (SA) under operationally relevant conditions, namely a noisy aircraft environment. Specifically, we sought to compare localization accuracy for three-dimensional (3D) audio, tactile, and audiotactile cues.

## Literature Review of Auditory and Tactile Cues During Aviation

Investigators have recognized the utility of 3D audio as a novel way of displaying information to pilots. Examples include Begault's (1993) work on 3D audio traffic collision avoidance systems (TCAS), Brungart and Simpson's (2005) multi-talker spatial communication technology, Simpson and colleagues' work on 3D audio navigation and attitude indicators (Simpson, Brungart, Dallman, Joffrion, Presnar, & Gilkey, 2005), and recent communication systems from Garmin International, Inc. (Olathe, KS). Flight is inherently spatial, occurring in three dimensional axes (lateral, vertical, and longitudinal), and the most intuitive spatial orientation cues should reflect this, making 3D audio a promising candidate technology for a non-visual SD countermeasure system.

Despite its potential, outstanding issues currently limit widespread adoption of 3D audio for military aviation. Perhaps the most significant concerns include mixed data regarding accurate cue perception and reduced effectiveness in noisy operational environments. Binaural hearing can facilitate sound localization within ten degrees of accuracy in the horizontal plane (Senn, Kompis, Vischer, & Haeusler, 2005), and some researchers claim minimal audible angles (MAAs) of one degree (or less) are possible (Perrott & Saberi, 1990). However, these data were obtained in quiet laboratory environments using discrete sound sources (i.e., speakers) rather than headphone-based 3D audio systems. A more applicable depiction may come from Brill and Scerra (2014), who evaluated localization accuracy for eight discrete azimuth cues, each separated by 45°. Although the spatial separation between cues greatly exceeded previously published MAAs by at least 25° (see Brungart, Durlach, & Rabinowitz, 1999), localization accuracy only averaged 75%, primarily due to fore-aft reversals affecting three forward positions (0°, -45°, +45°). Brill and Scerra (2014) concluded the disparity between their results and previously published data were the result of leaving in common perceptual errors, namely fore-aft reversals, which are typically excluded from data analyses. They proposed the inclusion of fore-aft reversals was critical for accurate assessment of localization performance.

The second major concern about 3D audio in the cockpit is noise, particularly in military aircraft. In-cabin noise levels can reach 102 dB for a UH-60 "Blackhawk" helicopter, making it an extremely noisy environment. Even if 3D sound levels compensate for ambient noise, it is unclear exactly how it will affect sound localization. Good and Gilkey (1996) found that noise decreased localization accuracy for the frontal plane (i.e., fore-aft) the most. Lorenzi, Gatehouse, and Lever (1999) found similar results. They tested sound localization for high and low-frequency cues in the presence of noise and found decreased performance for the zero-degree position, irrespective of cue frequency. These results suggest frequency-based signal compensation may be of limited utility.

Tactile cues can be used as a potential alternative or supplement to 3D audio. Like hearing, touch is spatial by nature. Otherwise, we would not be able to find an itch, an insect crawling on us, or respond in the direction of a tap on the shoulder. Rupert's (2000) Tactile Situation Awareness System (TSAS) takes advantage of a tap-on-the-shoulder metaphor to provide pilots with spatial orientation cues, ranging from an Earth-centric vector (i.e., which way is down) to navigation and spatial alarms (e.g., TCAS or incoming missile). Others have developed systems based upon the TSAS theme, including Van Erp and colleagues (2006) and Rochlis (Rochlis & Newman, 2000).

Localization of torso-based tactile cues can be comparably better than 3D audio, although it greatly depends upon the circumstance. Localization accuracy for an 8-tactor circular array (i.e., belt around the torso) is 92-94% (Brill & Scerra, 2014; Cholewiak, Brill, & Schwab, 2004). However, accuracy drops with larger arrays (e.g., 74% for a 12-tactor circular array; Cholewiak et al., 2004). Whereas inaccuracies for 3D audio affect the fore and aft positions, tactile mislocalization occurs most frequently on the sides of the abdomen. Moreover, if a tactile cue is misperceived, it is typically by a single position, meaning the greatest possible error is 45° (compared to 180° for 3D audio). A comparison of localization performance for 3D audio and tactile cues reveals non-overlapping cones of confusion (Brill & Scerra, 2014). In essence, each modality's strength can potentially complement the other's weakness. Consequently, redundant bimodal cueing may yield greater performance than either modality alone.

## Present Study

The present study sought to evaluate the relative effectiveness of spatial 3D audio, tactile, and combined "audiotactile" cues in the presence of noise. To improve external validity, we used a realistic operation noise stimulus: a recording of a UH-60 helicopter. It was predicted that localization accuracy and response times would be best for tactile and audiotactile cues; however, no specific predictions for relative differences between tactile and audiotactile cues were made.

# Method

## Participants

The experiment was reviewed and approved by Institutional Review Boards from the U.S. Army Medical Research and Materiel Command and Old Dominion University prior to participant recruitment. The participants provided written informed consent. A sample of eleven volunteers (10 males, 1 female, mean age = 31.5 years) was recruited from personnel at the U.S. Army Aeromedical Research Laboratory (USAARL) at Ft. Rucker. All had normal hearing, as confirmed by a hearing test, and normal sensorimotor functioning.

## Research Design

The experiment used a within-groups design, wherein signal modality comprised each of the three conditions: auditory, tactile, and audiotactile. A within-groups design was adopted to control for potential individual differences in perception. Moreover, the nature of the experimental tasks (i.e., simple perceptual judgments) raised little concern regarding potential learning or carryover effects.

## Apparatus

All signal presentation and data collection was performed using SuperLab 4.5.4 (Cedrus, Inc., San Pedro, CA) running on an MS-Windows-based laptop computer with an optical mouse. The software was setup to display on-screen instructions, present all experimental stimuli, and capture participant responses in milliseconds. The computer controlled the tactile display (see below) by sending serial strings via a USB cable. Ambient noise (90 dB) was provided by playing a digital audio recording of a Sikorsky UH-60 "Blackhawk" helicopter in flight. The sound file was played on a desktop computer connected to a QSC model PLX-3602 stereo audio amplifier and Electro-Voice (EV) model T251+ speakers. The tactile display was comprised of an Engineering Acoustics, Inc. (EAI; Casselberry, FL) 8-tactor belt with model ATC3 controller. The belt was populated with model C2 tactors, speaker-like linear actuators for transmitting vibration into the skin. It was worn around the abdomen and secured with hook-and-loop material for a slightly snug fit for mechanically loading the tactors against the skin. The tactors were driven with a 250 Hz sinusoid at 90% power, which correlates to 51 dB, and activated for 500 ms. At this intensity, the vibrotactile pulses are easily detectable. The pulses are similar to vibration from a cell phone, but stronger and more focused. The tactile pulses were presented at eight discrete egocentric positions at 45-degree spacing: 0°(center ahead), 45°, 90° (right), 135°, 180° (aft), 225°, 270°(left), 315°.

The 3D audio display consisted of a laptop computer with a soundcard and Sennheiser HD-201 headphones for the playback of 3D spatialized digital audio files. The audio files consisted of 500 ms 150 Hz clicktrains that were processed using NASA SLAB Spatial Audio Renderer 5.8.1. They were rendered for eight azimuth positions. Each was equidistant from a central point so as to encircle the listener with discrete egocentric cues with the same 45-degree spacing as used for the tactile display. The loudness of the audio cues was calibrated using the method of adjustment in the presence of helicopter noise. A sample of five pilot participants were presented with an alternating pattern of 3D and vibrotactile signals with the task of adjusting the loudness of the 3D audio signals (using a volume knob) to match the subjective intensity of the vibrotactile signals. Each pilot participant performed the match eight times, and the average intensity value was calculated. Then, the grand mean was calculated and served as the intensity used for all study participants. Audiotactile signals were generated in a similar manner, through simultaneous (redundant) cueing via the 3D audio and tactile displays.

## Procedure

Participants were welcomed to the laboratory and written informed consent was obtained. A hearing test was administered and participants were classified as having "normal" hearing if they met ANSI S3.19-1974 (ANSI, 2007). Participants were then led to a sound isolation booth and fitted with the tactile display. They were then seated in an ergonomic "kneeling" chair at a computer workstation and given an overview of the experimental task with exemplar stimuli. They were told they would be presented with a random series of audio, tactile, and audiotactile signals. They were asked to use the computer mouse to click a box on an on-screen graphic to indicate the perceived signal location. The graphic consisted of a top-down view of a human head encircled by eight boxes representing stimuli loci. Once the participant was ready to begin the experimental tasks, the experimenter left the room and began helicopter noise playback. Whenever a signal was presented, the participant would click a box to register a response. The timing of signal presentation was variable using a randomly selected inter-trial interval (2.5, 3.0, or 3.5 s) to prevent participants from getting into a response rhythm. Signals were grouped in three blocks, each comprising a modality condition. A block consisted of ten presentations of each of the eight stimulus locations, in random order, for a given sensory modality, resulting in 80 trials per block. The order of blocks was counterbalanced using a Latin Square design. After completing all three blocks, participants were thanked for their participation and dismissed from the study.

# Results

As the sample is relatively small, we chose a conservative approach to hypothesis testing by using non-parametric statistics with an alpha of .05. The data were screened for outliers, and one participant was removed for highly anomalous data, suggestive of equipment malfunction. This left a sample of ten participants for analyses. Raw performance data were coded and descriptive statistics were computed, including percent correct and mean response time by modality condition (see Table 1) and percent correct by stimulus position for each modality (Figures 1-3). To facilitate comparison, Figure 4 depicts 3D audio localization performance for the exact same cues when presented in a quiet environment (from Brill & Scerra, 2014).

Table 1.

*Mean Cue Localization Accuracy and Response Time (in ms) for Azimuth Cues by Signal Modality.*

| Modality | Percent Correct | RT Correct Reponses | RT Errors |
|---|---|---|---|
| Audio | 53.1% (16.3%) | 1773 (89) | 1560 (429) |
| Tactile | 91.3% (6.3%) | 1230 (645) | 1867 (505) |
| Audiotactile | 92.8% (5.3%) | 1238 (170) | 1546 (182) |

*Note:* Standard deviation is in parentheses.

Figure 1. *Percent Correct for 3D Audio Cues by Location*

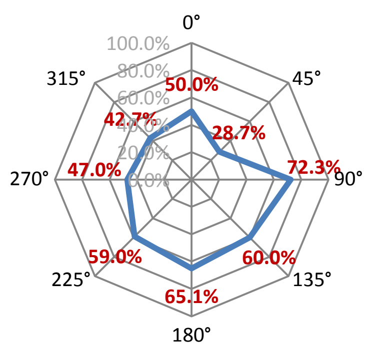



Figure 2. *Percent Correct for Tactile Cues by Location*

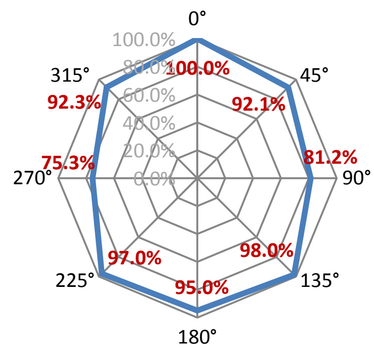



Figure 3. *Percent Correct for Audiotactile Cues by Location*

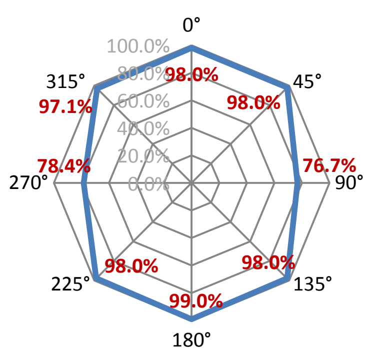
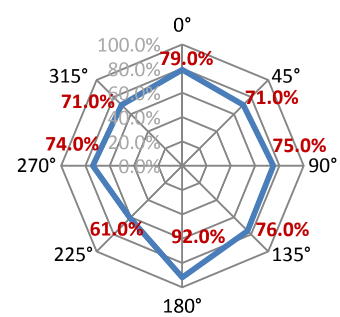



Figure 4. *Percent Correct for Audio Cues by Location (Quiet Environment)*




*Figures 1-3.* Percent correct localization under different cueing conditions (top-down view of eight tactors around torso).

A nonparametric test of differences (Wilcoxon Signed Rank Test for Related Samples) confirmed the hypothesis that localization accuracy (percent correct) was substantially better for tactile ($M$ = 91.3) and audiotactile cues ($M$ = 92.8) versus 3D audio cues ($M$ = 53.1) ($ps$ < .01). Likewise, mean response time for correct responses was significantly faster for tactile ($M$ = 1230) and audiotactile ($M$ = 1238) cues versus 3D audio cues ($M$ = 1773) ($ps$ < .01). However, no differences in response time were observed for errors ($p$ > .05).

## Discussion

The purpose of this investigation was to conduct a pilot study of the effects of operational helicopter noise on localization of discrete spatial audio, tactile, and redundant audiotactile cues in adult humans with normal hearing. Participants were, on average, 39% more accurate and 70% faster in responding to tactile or audiotactile cues versus 3D audio alone. This dramatic disparity does not just represent a statistically significant difference, but it is also a *meaningful* difference. Loud ambient noise had a dramatic effect on 3D audio performance, particularly for frontal positions, reminiscent of results by Good and Gilkey (1996) and Lorenzi et al. (1999). Nevertheless, our data exhibited an overall suppression of accuracy, whereas Lorenzi's frequency manipulation facilitated improved 3D audio performance for lateral positions. The signal we used was a 150 Hz clicktrain which was psychophysically calibrated for clear audibility above the ambient noise. However, we have yet to explore frequency-based manipulations to improve 3D audio performance. The data from this investigation will serve as a baseline for evaluating the effectiveness of frequency modulated 3D audio signals. To this end, signals representing lateral positions could be modified to contain more high frequency content to facilitate performance improvements.

Our data also suggest simultaneous vibrotactile cueing can effectively eliminate the spatial cueing inaccuracies common with 3D audio. For the human perceiver, the redundant tactile cue can help resolve ambiguity and uncertainty by providing a second piece of concordant information, particularly for positions for which perceptual reversals are likely. As in the real world, perception is rarely unimodal. We use our senses to collect multimodal information, and each sensory modality provides more information to assist perceptual guesses. The more information that is available, the less of a "guess" we make. It is the difference between seeing a friend from afar versus up close. You think the person is your friend, but it could be someone who resembles her. If she is at a distance and just standing, you can easily make an incorrect guess. In contrast, if she is a shorter distance away and you can observe her gait and hear her voice, the situation is much more data-rich to aid with identification.

Despite the impressive results of this pilot investigation, caution should be taken, as this is an ongoing investigation and more research will allow us to explore these questions further with larger sample sizes. At this stage, our results should be considered preliminary and subject to confirmation through further research. Current work is expanding the research presented here to include more azimuthal positions, elevation cues, and a second participant population: pilots with noise-induced hearing loss. Noise-induced hearing loss is a well-recognized and ongoing problem for military pilots. Pilots with hearing loss will likely have even worse 3D audio localization performance than those with normal hearing. We seek to evaluate if redundant tactile cueing is as effective for them as it is for a normal hearing population.

Given that performance for tactile cues was indistinguishable from audiotactile cues, one might suggest, why not simply use tactile cues as an alternative rather than a supplement? The answer is two-fold. First, incorporating audio and tactile cueing systems could offer a form of backup through redundancy in the event of system failure. Second, 3D audio is capable of presenting more than just noise bursts and tones. Earcons, the auditory equivalent of an icon, could be presented to aid with signal differentiation. Rather than using both touch and hearing for the equivalent of a tap-on-the-shoulder, the vibrotactile system could provide the tap, and the 3D earcon could convey target identity while also providing a concurrent directional cue.

To summarize, we presented 3D audio, tactile, and audiotactile azimuth directional cues to ten participants in the presence of 90 dB helicopter noise. Performance for tactile and audiotactile cues was significantly faster and more accurate than 3D audio cues alone. The data suggest tactile and audiotactile cues provide viable alternatives for counteracting spatial disorientation by improving pilot situation awareness.

## Disclaimer

The views and opinions of authors expressed herein are those of the authors and do not necessarily state or reflect those of the United States Government or any agency thereof. This research was funded by U.S. Army Medical Research and Materiel Command. Dr. Angus Rupert is the principal investigator.

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