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Head-Up Auditory Displays for Traffic Collision Avoidance System Advisories: A Preliminary Investigation

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The advantage of a head-up auditory display was evaluated in a preliminary experiment designed to measure and compare the acquisition time for capturing visual targets under two auditory conditions: standard one-earpiece presentation and two-earpiece three-dimensional (3D) audio presentation. Twelve commercial airline crews were tested under full mission simulation conditions at the NASA-Ames Man-Vehicle Systems Research Facility advanced concepts flight simulator. Scenario software generated visual targets corresponding to aircraft that would activate a traffic collision avoidance system (TCAS) aural advisory; the spatial auditory position was linked to the visual position with 3D audio presentation. Results showed that crew members using a 3D auditory display acquired targets approximately 2.2 s faster than did crew members who used one-earpiece headsets, but there was no significant difference in the number of targets acquired.

INTRODUCTION

The current implementation of the traffic alert and collision avoidance system (TCAS II; referred to as TCAS in this paper) uses both auditory and visual displays of information to supply flight crews with real-time information about closely proximate aircraft. However, the visual display is the only component that conveys spatial information about surrounding aircraft; the auditory component is used as a redundant warning or, in the most critical scenarios, for issuing instructions for evasive action.

Three categories of visual-aural warnings are activated by TCAS as a function of an intruding aircraft's calculated distance and/or time to impact (Air Transport Association Flight Systems Integration Committee, 1989). The first category—for *proximate* and *other traffic*—is informational, and the TCAS system uses only a visual display. In this case TCAS functions more as a situational awareness system than as a warning system. The second category—*traffic advisories*—consists of cautionary alerts. The threshold for activating a traffic advisory is a collision calculated to occur within 40 s; an amber-filled circle is generated on a visual map display, and an auditory warning is given that consists of a single cycle of the spoken words, "traffic, traffic." The third category—*resolution advisories*—usually requires corrective, restrictive, or preventive motion by

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the pilot and is activated by traffic calculated to impact within 20–25 s. Audio is used to indicate the appropriate evasive action (e.g., "climb, climb, climb").

In the present experiment the aural component of the TCAS advisory—the alert, "traffic, traffic"—was modified to convey the spatial information normally obtained only through visual instrumentation. In this way the audio component served both an alert function and a spatial orientation function simultaneously, and the visual component was eliminated. No visual TCAS symbology, resolution advisories, or other types of information were displayed. A between-subjects experimental design was used to measure the time taken to visually acquire out-the-window targets, with and without the use of auditory spatial cues linked to the direction of visual search. The experiments were conducted with current commercial airplane pilots in the context of a full mission simulation.

A finding that motivated the current investigation into an auditory TCAS display was reported by Chappell et al. (1989) in their full-mission evaluation of TCAS. They used four conditions for displaying information about the location of other traffic: (1) a control condition with no TCAS display or audio alert, (2) a minimal TCAS display with visual and auditory alerts but no location information, (3) a TCAS display with traffic shown during conflicts, and (4) a TCAS system as currently implemented on U.S. air carriers, with a continuous traffic display. The results of the study showed that among the three TCAS display conditions, there were no significant differences in the number of targets acquired or in the time or type of response to the TCAS resolution command. In summary, Chappell et al. found that there was no additional benefit of providing pilots with a head-down planform display of traffic information.

Perrott, Saberi, Brown, and Strybel (1990), however, found that the presence of information from an auditory source substantially reduced the time to acquire and identify a visual target. They hypothesized that "the primary function of the auditory spatial system may be to provide information that allows the individual to redirect the eyes in order to bring the fovea into line with an acoustically active object" (p. 214). In their experiments they compared within-subjects acquisition latencies using a 10-Hz click train from a speaker that was either spatially correlated or uncorrelated with a target light. In one experiment they examined target acquisition over a wide range of azimuths (±130 deg) at an elevation matched to the initial line of gaze. For targets at 0 deg azimuth, the mean improvement in acquisition time for the spatially correlated condition was 150 ms. For targets around 120 deg azimuth, the mean improvement was 700 ms. A second experiment that varied both azimuth (±130 deg) and elevation (±46 deg) of the targets showed that at 0 deg, the spatially correlated condition improved acquisition time by about 500 ms; for targets at 120 deg azimuth, mean improvement was about 1200 ms.

The present study evaluated the feasibility of using a head-up auditory display for providing the spatial information that is usually communicated via a head-down visual display. Two groups consisting of six crews each were evaluated: a three-dimensional (3D) audio experimental group, with spatial sound correlated with out-the-window target direction with reference to a forward head position; and a monotic control group, for whom interaural level and time differences were removed from the audio display and signals were transduced to one ear only. It was hypothesized that acquisition time might be reduced if spatial audio cues were used to guide the head and/or eyes toward the direction of the target. The present study also explored the use of 3D sound technology, in which source positions in auditory space are simulated via headphones. This technique differs from the Perrott et al. (1990) experiment in that they used a moving loudspeaker for their sound source.

Several researchers, including Doll, Gerth, Engelman, and Folds (1986), Sorkin, Wightman, Kistler, and Elvers (1989), and Begault and Wenzel (1992), have suggested several applications for the use of 3D sound in the cockpit, including target acquisition. The study by Sorkin et al. (1989) used a magnetic head tracker in conjunction with a 3D sound device within a simple cockpit mock-up. The focus of their study was to compare localization accuracy (rather than target acquisition time) under conditions in which head movement was either correlated or uncorrelated with the 3D audio display. The visual targets in their study were a set of 52 numbered positions on a fixed screen, within an azimuth arc of 270 deg and an elevation arc of 54 deg. Their results showed that the accuracy of azimuthal localization was improved when head movement was correlated with the 3D audio display but that elevation localization accuracy was poor, independent of the condition. The current study used only azimuth cues, and no correlation between head movement and the 3D audio display was used.

EXPERIMENT

Method

Subjects. Twelve two-person flight crews served as subjects for this study. Crews were current airplane pilots employed by the same major U.S. air carrier, and all were rated in a "glass" cockpit aircraft (e.g., Boeing 757, 767). Each crew member was paid a small amount for participating ($12.50/h). Because all crew members were currently active, they had been previously evaluated for normal hearing within the last year (first officers) or six months (captains) by company and Federal Aviation Administration medical examinations.

Experimental design. Two conditions—one with and one without spatial sound cues linked to out-the-window visual targets—were evaluated in a between-subjects design. The experimental group, consisting of 6 two-person crews with stereo headsets, heard a binaurally processed version of the advisory (the 3D sound condition). The perceived direction of the auditory advisory for this group was adjusted to correspond to the azimuth of the target out the window. A control group, also consisting of 6 two-person crews, heard the same warnings; however, these warnings were mixed to one earpiece of the headset (the monotic condition), which removed the binaural interaural time and intensity cues and probably removed any monaural cues that would be usable under the experimental conditions. The 12 crews were assigned randomly to either the 3D sound or the monotic sound condition. The dependent variable was the interval between the triggering of a visual target in conjunction with a TCAS aural advisory and the verbal response from a crew member indicating acquisition of the target. The number of targets acquired was also a dependent variable.

The crew members were instructed to call out when they had visually acquired the aircraft out of the window (a consistent utterance, such as "got it!"). Acquisition times were calculated as the difference between the time the visual target was generated in the scenario software and the beginning of the verbal utterance acknowledging target acquisition, as observed on videotapes by the experimenter. A record was kept of the number of targets acquired as well. Temporal information was obtained by correlating scenario clock times with the time code generated on the videotapes. The accuracy of the experimenter's determination of the beginning of the verbal utterance was found to be within two video frames (0.066 s). Target acquisition times and the number of targets acquired were categorized according to whether the target was visible to both crew members or to only one.

The experiment ran concurrently with an automated checklist experiment (Palmer and Degani, 1991). The checklist experiment involved two conditions: one with displays operated via a touch panel, and a control condition using a standard checklist. Initially the monotic and 3D sound conditions were counterbalanced with these checklist conditions, but failure of the target generation system for one crew prevented complete counterbalancing. Consequently, the checklist type is considered here to be a random element. Indeed, in actual flight, checklist activity would normally be subordinate to traffic acquisition in response to a TCAS advisory, except in emergency situations.

Available field of view. A substantial limitation inherent in all flight simulators is the available out-the-window field of view for each pilot. The simulator used in this experiment was a modified Lockheed-Georgia cockpit equipped with a Singer-Link Advanced Simulator Technology visual system. It had a three-channel, four-screen system (*channel* refers to a discrete display of visual information). The two center screens in the simulator displayed an identical visual scene; each was visible to only one pilot. Each pilot utilized two screens: a center screen with a field of view common to both pilots extending to ±15 deg azimuth, and a side screen with a field of view unique to each pilot that extended the field of view to ±52 deg azimuth.

Figure 1 shows the field of view for the captain's side (left) along the inner semicircle; the first officer's view would be the mirror image of this figure. The immediate azimuthal field of view extended from about −40 to +15 deg, but with head and body

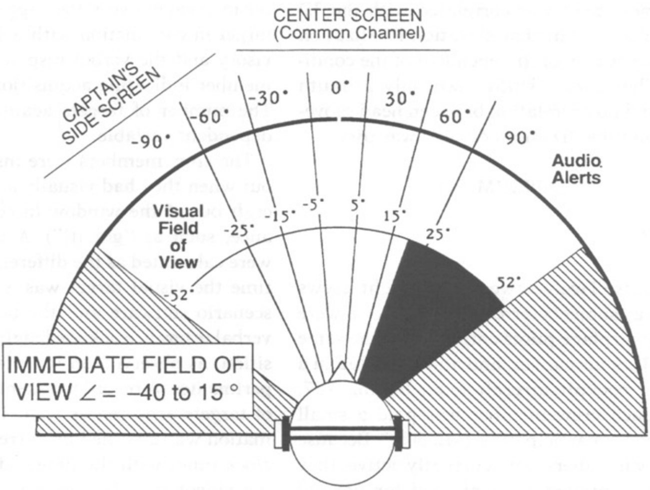

Figure 1. *The horizontal field of view in the simulator, from the perspective of the left seat (captain's position). The outer semicircle shows the mapping between visual azimuths and the position of the 3D sound cue.*

movement, the entire available range over the left and center screens ranged from −52 to +20 deg. (The current experiment restricted the range of target azimuths to ±35 deg.) Note that the field of view from 20 to 52 deg was available only to the first officer, whereas the area of ±15 deg was available to both crew members.

Figure 2 shows the vertical field of view; the immediate range is from about −13 to +16 deg but can extend from −18 to +20 deg with head and body adjustments. For reference, the visible range of a target at 3 miles is shown in terms of relative elevation (in feet) above or below the simulator. In this experiment all targets were restricted to the immediate vertical field of view.

Stimuli. A set of 24 targets was specified within the scenario software and was used for all crews. The azimuths of the target set were randomly chosen within three visual angles: 12 within ±15 deg, visible to both crew members; 6 within −35 to −20 deg, visible only to the captain; and 6 within 20 to 35 deg, visible only to the first officer. Distances and elevations for each target varied within fixed ranges: between −2000 and 3000 feet for relative elevation and between 2 and 5 miles distance. Figure 3 shows the azimuth and elevation of the resultant target set used for each crew. The open triangles in Figure 3 represent the 12 targets visible to both crew members, and the solid triangles represent targets visible to only one crew member.

Figure 1 shows the visual field of view divided into seven angles, with edges at −25, −15, −5, 5, 15, and 25 deg. A target activated one of seven spatial auditory warnings, depending on which angle it fell within. In a preliminary evaluation of the 3D sound TCAS system, it was found that when the 3D angle of the auditory warning was multiplied by three (based on the center point of the angle in which the target was located—i.e., 0, ±10, ±20, and ±30 deg), a more convincing suggestion was given of which direction to search than was provided by one-to-one mapping.

There are three reasons for using audio positions that exaggerate visual positions. The first is pragmatic: measurements for the 3D sound system exist only for every 15 deg of azimuth; other positions must be obtained through interpolation, a process that has not been completely psychoacoustically verified for localization accuracy. If exaggerated audio positions had not been used, the entire visual space would have been mapped to a limited arc. Second, discrimination (as opposed to localization) between positions separated by 15 deg is more difficult than that between positions separated by 30 deg. This is supported by localization studies that show that the average azimuth estimation error for spatialized speech is about 8 deg for a target at 30 degrees (Begault, 1992).

Finally, the use of 30-, 60-, and 90-deg azimuths utilizes the full range of interaural time delays that the auditory system interprets in terms of left-right displacement. The literature is in general agreement that a headphone source stops moving to the side of the head when a time delay exceeds approximately 1 ms (Blauert, 1983). Figure 4 shows averaged interaural group delays at the relevant azimuth positions (based on ⅓-octave analysis of speech frequencies: 100 Hz–6 kHz), which best approximate interaural time delays for the simulated positions used in the current experiment. A 3D audio TCAS system that used one-to-one mapping would use interaural time delay only up to 0.2 ms (the triangles in Figure 4), whereas exaggeration by a factor of three utilizes delays up to 0.7 ms (the arrows in Figure 4).

Targets were *ballistic,* meaning that each was assigned a bearing and relative speed (from 0.8 to 1.2 times the speed of the simulator). This gave the targets a greater sense of realism, but it also meant that the direction

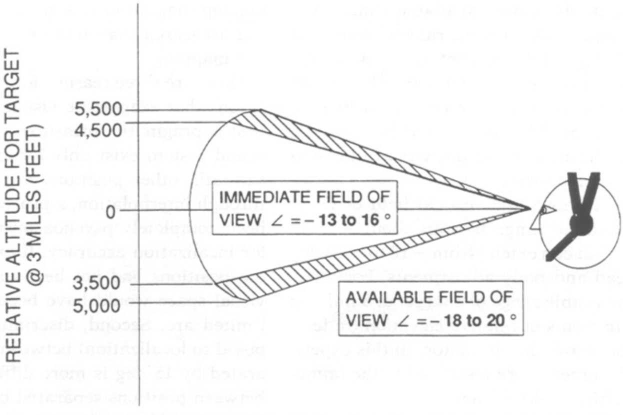

Figure 2. *The vertical field of view in the simulator, based on the relative altitude of an aircraft at 3 miles' distance.*

of the targets in the visual field was random across crews, once the target had appeared at its fixed initial start point. To compensate for this, an algorithm was included in the experimental software that adjusted the azimuth warning used in terms of the relative bearing and speed. For instance, if the target start point was at 16 deg, it was technically within the 15- to 25-deg azimuth angle; if its ballistic characteristic caused it to move to the 5- to 15-deg angle within 1 s, however, it was considered to be within the 5- to 15-deg angle for the TCAS system.

Aural TCAS advisories; 3D sound processing. The method for implementing a 3D auditory display was based on the use of digital filters that capture the magnitude and phase characteristics of the head-related transfer function (HRTF)—that is, the listener-specific, direction-dependent acoustic effects imposed on an incoming signal by the pinnae (see, e.g., Begault and Wenzel, 1992; Wenzel, Wightman, and Foster, 1988). HRTF measurements made near the tympanic membrane of the listener show conspicuous changes as a function of different source positions, in tandem with changes in interaural level and time differences. The pinnae's complex filtering provides a principal cue for localization, particularly for sources on the median plane (Blauert, 1983; Searle, Braida, Cuddy, and Davis, 1976). The use of HRTF filtering is also considered a primary determinant for externalizing headphone-delivered sound (Plenge, 1974; Wightman, Kistler, and Perkins, 1987). Basic research on the perceptual error inherent with 3D sound simulation has only a recent history (see, e.g., Begault and Wenzel, 1993; Wightman and Kistler, 1989).

The aural alert "traffic, traffic" was digitally recorded by a male speaker in a soundproof booth using an electrostatic microphone (AKG 451-EB), preamplifier (Symetrix SX-202), and digital audiotape (DAT) recorder (Panasonic SV-3500). The total duration of the alert was 2.8 s: 800 ms for the word "traffic," a 1-s silent interval, and another 800-ms "traffic." The average spectrum of the word "traffic" is shown in Figure 5. This recording was transferred to a desktop computer

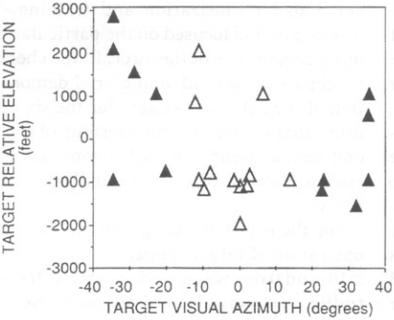

Figure 3. *The relative elevation and azimuths of the 24 targets used in the experiment. Solid triangles represent targets visible to only one crew member; open triangles represent targets visible to both crew members.*

(Macintosh IIcx) using audio recording software and hardware (Digidesign's ProTools), at a sampling rate of 50 kHz. Next, the aural alert was convolved with HRTF measurements at four spatial auditory positions: 0

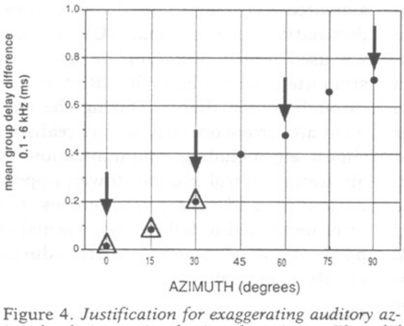

Figure 4. *Justification for exaggerating auditory azimuth relative to visual azimuth positions. The solid circles show the mean interaural group delay difference for speech frequencies at selected azimuths, measured from the HRTFs used in the present experiment. The maximum value on the vertical axis (1 ms) corresponds to maximal lateral displacement. Triangles indicate the auditory azimuths that would be used without exaggeration of visual stimuli positions; arrows point at the mean interaural difference with exaggeration (as done in the current experiment).*

(directly in front of the listener), left 30, 60, and 90 deg azimuth, all at 0 deg elevation. Positions for right 30, 60, and 90 deg were obtained by reversing the output channels at playback, resulting in a total of seven available spatialized positions.

The HRTFs were obtained from Fred Wightman and Doris Kistler of the University of Wisconsin-Madison; these were 50-kHz sample rate, 16-bit floating-point anechoic measurements of subject SDO (see Wightman and Kistler, 1989, for further details). These measurements have a frequency response between 200 Hz and 14 kHz. The convolution was performed in nonreal time on the desktop computer by supplying formatted versions of the measurements to a standard signal processing package (Zola Technologies' DSP Designer). The resulting signals were then converted to a 33.3-kHz sample rate in 12-bit signed integer form and subsequently stored in an audio playback device (Yamaha TX-16W stereo sampler). The stimuli were played back in coordination with the scenario software via "note on/off" commands inherent in the musical instrument digital interface (MIDI) specification.

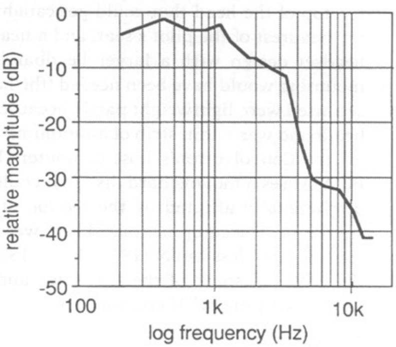

Figure 5. *Average spectrum of the speech alert, "traffic," used in the experiment (256-point fast Fourier transform).*

Pilots wore headsets (Sony Walkman style MDR-M22, modified with a microphone) that were selected for comfort and fidelity. Their frequency response ranged between 20 Hz and 16 kHz, and their weight was about 31 g. The headset had a supra-aural design, meaning that the transducers rested on the outside of the ears, allowing outside conversation to be more easily monitored than with a circumaural design. Playback of the alert was at about 74 dB SPL at the ear; the simulator's ambient background noise was about 70 dB SPL ("c" weighting) measured in the center of the cockpit. The spectrum of the ambient sound was approximately that of white noise (for wind simulation), combined with engine sound simulations.

No head-tracking device (such as a Polhemus 3-Space Isotrak) was used to couple the spatial display to head position, as is possible with, for example, a Convolvotron 3-D audio display device (see Wenzel et al., 1988). Although this was considered at the outset, it was ultimately rejected because (1) magnetic sensors can provide distorted positional information as a result of closely proximate metal surfaces within the cockpit; (2) the sensors would require an additional cable from the top of the head that could get caught on the headrest of the pilot's seat, and a heavier headset design with a larger headband for mounting would have been needed (the headsets used were lightweight partly because the headband was a thin strip of aluminum); and (3) the Convolvotron's host computer (IBM PC-AT) uses a moving hard disk that could be detrimentally affected by the motion of the simulator. The equipment used here was also considerably less bulky (19″ × 14″ × 13″) for the confined space of the simulator and allowed real-time MIDI control.

Procedures

Training. Each crew spent two days at the simulator, with the first day and a half devoted to familiarization and training. The training period focused on the particular handling capabilities of the aircraft, the checklist procedure to be used, and a brief demonstration of the 3D audio system for the six crews using that system. On the morning of the second day, a round-trip flight from San Francisco to Sacramento was the final training activity.

For the experimental group, a 2-min demonstration of targets appearing at ±30, ±20, ±10, and 0 deg was shown, with the 3D audio traffic alert played simultaneously. No other information was given to the pilots about the nature of the experiment.

Scenarios. The two-person crews flew the experimental flights on the afternoon of the second day. The scenario consisted of three flight segments, or flight legs, with an overall duration of about 3.5 h: San Francisco-Sacramento, Sacramento-Stockton, and Stockton-San Francisco. Nine targets were distributed across the first and last legs and six across the shorter, second leg. These were activated according to the distance from the destination. Conventional VOR navigation was used by all crews; complete darkness was simulated, with about 50 miles visibility throughout the flights. During the experiment all normal operations were realistically simulated, including communications with air traffic control ground, tower, approach, departure, and center frequencies. Crews were instructed to follow their normal company standard operating procedures as closely as possible.

Results

A target was considered to have been acquired if the crew obtained it within a 15-s time window, which is the limit before the traffic could potentially be elevated to "traffic resolution" status. Only two targets were acquired outside this time window (by two different crews under the monotic condition);

these were clearly outliers (20 and 23 s) and were therefore excluded in the subsequent analysis. (Their inclusion did not affect the significance levels in the analysis.)

Figure 6 shows the mean target acquisition times for the monotic and 3D sound conditions: 4.7 s (*SD* 1.9 s) and 2.5 s (*SD* 0.8 s), respectively. An analysis of variance showed a significant difference in the mean acquisition times, $F(1,10) = 17.0, p = 0.002$, but no significant difference was found as a function of whether the targets were visible by both crew members or by one crew member, $F(1,10) = 2.7, p = 0.130$. In addition, no significant interaction between visible angle and condition was found $F(1,10) = 0.9, p = 0.359$. A significant difference was found between acquisition times, depending on flight leg, across both conditions, $F(2,20) = 7.3, p = 0.004$ (see Table 1). However, there was no significant interaction between flight leg and experimental condition, $F(2,20) = 2.4, p = 0.118$.

These results could have been skewed if a disproportionate amount of targets were acquired under one condition. Also, if significant differences were found in the number of targets acquired from the field of view common to both crew members (±15 deg), compared with those in the field of view of one crew member (>20 or < −20 deg), the acquisition time improvement may have favored certain azimuths. However, the analysis of variance showed no significant difference in the number of targets acquired according to condition, $F(1,10) = 1.3, p = 0.273$, target azimuth grouped by field of view, $F(1,10) = 0.02, p = 0.894$, or interaction between the two variables, $F(1,10) = 0.02, p = 0.894$. The overall number of targets acquired is shown in Table 2.

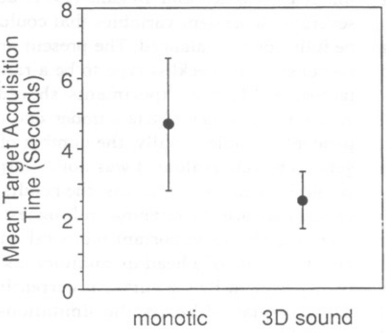

Figure 6. *Means and standard deviations for target acquisition with and without 3D sound presentation.*

TABLE 1

Acquisition Times Collapsed across Experimental Conditions, by Flight Leg

Leg	Mean	*SD*
1	4.0	1.7
2	2.3	1.1
3	5.0	3.6

CONCLUSIONS

The most important finding in the analysis is that the presence of a spatial auditory cue can significantly reduce the time necessary for visual search. A difference of about 2.2 s was found, which could potentially be a critical advantage in maneuvering an aircraft away from oncoming traffic. The advantage found here of combining visual and auditory spatial information is generally in line with results found in the more controlled laboratory experiments of Perrott et al. (1990). The difference between the 1.2-s advantage

TABLE 2

Breakdown of Total Number of Targets Acquired out of 24 Possible

Condition	Mean	*SD*
Monotic	15.8	3.6
3D sound	17.5	3.3
Combined	16.66	3.3

There was no significant difference between conditions.

observed by Perrot et al. and the 2.2 s difference observed here could be attributable to the fact that targets in the current experiment were ballistic and were acquired within the context of a full mission simulation.

The reduction in acquisition time found here contradicts the results of Chappell et al. (1989) in one sense. They investigated head-down planform displays with different levels of detail and measured the time for taking evasive action. No significant time differences were found as a function of the detail of the display. Audio is essentially a "head-up" display, but the difference between looking down at a planform display and then out the window and looking out the window immediately does not sufficiently explain the reduction in acquisition time in the present experiment. The reduction in acquisition time was enhanced by the addition of directional information to the auditory alert, not merely its head-up characteristic.

One explanation for the experimental outcome reported here could lie in the limitations of field of view within the flight simulator. Unlike actual cockpits, the field of view in the simulator is such that the person sitting on the left side cannot see beyond 15 to 20 deg to the right, and the person on the right side cannot see beyond 15 to 20 deg to the left. Therefore it is possible that the spatial auditory cue was used in estimating target positions in a crude way in order to transcend the limitations of the simulator environment: that is, if it sounds to the right, the first officer searches, and if it's to the left, the captain searches. This is indicative of a task delegation procedure. However, in actual operations contexts, most search is usually by the pilot not flying, depending on the phase of flight and the relative urgency of the TCAS alert. Even if this trade-off feature were not an element, the spatial auditory cue could still have been utilized as a crude means of determining where to begin visual search. If it is true that the spatial sound cue provides a general direction for search that is subsequently refined by visual search, then the additional azimuthal accuracy provided by a head-coupled 3D auditory display (Sorkin et al., 1989) might be unnecessary.

There was no significant difference in the number of targets obtained under either condition; hence the spatial auditory cue is unnecessary for capture of the target itself within the 15-s window of the TCAS advisory. This parallels the results of Chappell et al. (1989), which showed that little is added by augmenting TCAS with increasingly detailed spatial representations (in their case, head-down planform displays). The present result is also not surprising considering a pilot's awareness of the operational importance of responding to TCAS alerts.

Overall, the results presented here must be evaluated provisionally, for three reasons. First, the simulator's field of view is not equivalent to that in an actual aircraft; in spite of substantial efforts to ensure realism, parallel studies will need to be performed under controlled laboratory conditions and then compared with applications research. Second, the simultaneously run checklist experiment by Palmer and Degani (1991) added several independent variables that could not be fully counterbalanced. The present analysis considered checklist type to be a random factor, but future experiments should increase the number of trials under one independent variable. Finally, the number of targets each crew evaluated was not as large as would be ideal. Nevertheless, the results presented here are encouraging and suggest that there may be an important temporal advantage in the use of a head-up auditory display. An experiment by the author is currently under way that addresses the limitations described here.

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