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Visual Search Performance in a Dynamic Environment with 3D Auditory Cues

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VISUAL SEARCH PERFORMANCE IN A DYNAMIC ENVIRONMENT WITH 3D AUDITORY CUES

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

By

JOHN PAUL MCINTIRE
B.S., University of Dayton, 2005

2007
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WRIGHT STATE UNIVERSITY

SCHOOL OF GRADUATE STUDIES

January 26, 2007

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY John Paul McIntire ENTITLED Visual Search Performance in a Dynamic Environment with 3D Auditory Cues BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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ABSTRACT

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Visual Search Performance in a Dynamic Environment with 3D Auditory Cues.

Previous research on aurally-aided visual search has repeatedly shown a significant reduction in response times when displaying 3D auditory cues. However, the vast majority of this research has only examined searches for static (non-moving) targets in static visual environments. In the present study, visual search performance in both static and dynamic (moving) visual environments is examined with and without virtual 3D auditory cues. In both static and dynamic environments, and for all observers, visual search times were significantly reduced when auditory spatial cues were displayed. Auditory cues provided the largest benefits when the target initially appeared at farther eccentricities and on the horizontal axis. General practice effects were observed, but 3D auditory cues were immediately effective with little or no time needed for learning. Overall, the results suggest a similar and consistent performance benefit offered by 3D audio for both static and dynamic environments.

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I. INTRODUCTION AND PURPOSE

A primary concern of aircraft and motor vehicle operators is maintaining spatial awareness of the environment. Consider the multitude of factors that a pilot must attend to during flight, such as altitude, attitude, speed, direction, environmental features, or the presence of other aircraft. In high-workload or stressful situations like combat or search-and-rescue missions, the amount of spatial information that demands attention can easily become overwhelming. The traditional method of dealing with this issue has been to provide an operator with additional visual displays (e.g., heads-up displays or HUDs) that present spatial information about the distance, direction, or altitude of other aircraft, targets, or terrain. The problem with this strategy is that it often taxes an already heavily burdened visual system, increasing fatigue and workload, which can harm situational awareness and operator effectiveness.

Recent advances in auditory display technology have made the auditory channel an attractive option for the display of spatial information, thereby relieving some of the burden placed upon the visual system (McKinley & Ericson, 1995; Barfield, Cohen, & Rosenberg, 1997; Perrott, Cisneros, McKinley, & D'Angelo, 1996). Current research on 3D auditory displays suggests that providing spatial information with auditory cues can improve performance for navigation (Simpson, Brungart, Dallman, Joffrion, Presnar, & Gilkey, 2005; Lokki & Gröhn, 2005) and especially visual search tasks (Bolia, D'Angleo, & McKinley, 1999). To effectively aid visual performance with auditory displays in complex operating environments, it is vital that we understand both visual and auditory spatial perception and their interactions.

Visual vs. Auditory Spatial Perception

Humans can only see in detail near or within the central visual field, the fovea, where spatial resolution (acuity) is excellent. Westheimer (1979) found that observers could reliably discriminate immediate displacements of a small line (0.5 degrees) when it was moved laterally by only 10 to 12 seconds of arc. This discriminability is remarkable given that the spacing between photoreceptors in the fovea is at least 3 times larger, a phenomenon called *hyperacuity* (Wandell, 1995). Our peripheral vision can often be used to detect or even identify objects, especially if they are in motion, but the acuity in the periphery is extremely poor. For instance, at only 30 degrees in the periphery, spatial resolution is about 30 times worse than that of the fovea. In addition, a human's binocular visual field spans approximately 200 degrees horizontally and 135 degrees vertically (measured from central fixation), making only about half of the spatial world visible at any given time (Wandell, 1995). These facts imply that the field of view of the visual system, while impressive in terms of acuity near the fovea, is fairly restricted in terms of size.

In comparison to foveal vision, the acuity of the auditory system is relatively poor. Under optimal conditions, with broadband sounds coming from the frontal field, Yost (2000) notes that the minimum audible angle (MAA), a measure of auditory spatial resolution, is about 1 to 2 degrees (or 3600 to 7200 seconds of arc). Thus, the acuity of the auditory system is, at the very least, 360 times poorer than the acuity of the visual system (3600 seconds vs. 10 seconds, respectively). However, the auditory system is an *omni-directional* system; it can detect sounds from any direction in the environment, regardless of where an observer's head is pointed. In addition, the auditory system is considered to be a "24-hour" system, while the visual system generally requires a person to have their eyes open and to be awake for visual perception to occur. Therefore, the "field of view" in the auditory system is at least twice as large as the visual system. So, the auditory system has two distinct advantages relative to the visual system: it has a wider field of view and the ability to operate around the clock.

In addition, one of the evolved functional purposes of the auditory system is to guide the eyes to acoustic events via a reflexive *orienting response*. For instance, when someone hears a loud noise behind them, they immediately turn their head towards the sound and point their eyes at the perceived location of the sound. The fovea is then able to sample the region of interest so that the source can be identified and, if necessary, action can be taken (Perrott, Saberi, Brown, & Strybel, 1990). Thus, auditory displays have the possibility of conveying spatial information in a more natural and intuitive manner than traditional visual displays. All of these considerations suggest that overall spatial awareness could be effectively augmented or enhanced by displaying spatial information to the auditory system, especially for visual search tasks.

Visual Search

Our interactions with the world constantly require that we look for something, such as a set of lost car keys, a specific face in a crowd, or a word on a page, a task referred to as a *visual search*. Due to its applicability to daily life and its ubiquitous nature, visual search has been extensively studied by psychologists for more than 70 years; as early as the 1930's, Kingsley (1932) described the phenomenology of "search" behaviors. More recently, researchers have used visual search tasks to test theories about perception and cognition (e.g., Neisser, 1964).

The main variable of interest in a traditional laboratory visual search task is the amount of time it takes a participant to locate a visual target (the *response time* or *reaction time)*. Participants are placed in front of a visual display and a fixation cross is used to “center” the line of gaze so that a participant’s eyes always start a search from the same spatial location. When the participant signals that he or she is ready to begin, a timer is started, the fixation cross disappears, and a visual target is presented at a random location. As fast as possible, the participant visually scans the display and then indicates the acquisition of the target by pressing a button, which stops the timer. Often, the visual target is one of two types that the participant must identify, such as an “L” or an “R.” This two-alternative, forced choice (2AFC) design ensures that participants are actually doing the required task by forcing them to detect *and identify* some stimulus, not just detect the presence of a stimulus. Visual search tasks can be made more difficult by adding distracting visual stimuli, enlarging the search area, or making the defining visual features of the target smaller or less salient.

In military contexts, pilots and soldiers are often required to conduct visual searches of their spatial environment for targets of interest. One major problem surrounding visual search is that it can be time-consuming, and pilots rarely have time to conduct extensive visual searches of the sky or terrain during combat or search-and-rescue missions. In addition, sub-optimal viewing conditions experienced during darkness, flight through clouds, immersion in fog or dust, and intense brightness can make successful visual searches difficult or impossible. The demands placed upon the visual system can be overwhelming, increasing workload and fatigue while decreasing situational awareness and overall performance.

Many operating environments also require the use of the visual modality above all others, while auditory and other sensory modalities remain under-utilized or ignored. By cuing an operator on the location of a target using sound, visual search performance and overall spatial awareness could benefit greatly. Using auditory spatial displays should be especially advantageous in situations where a target could appear anywhere within a large search area, and the task requires both detection and discrimination of targets. These conditions can be found in many operating environments such as aircraft cockpits and ground-based vehicles.

Auditory Spatial Perception and Virtual Auditory Displays

Thanks to recent research and advances in technology, virtual (3D) auditory displays are able to *simulate* a spatial auditory environment when presented over normal headphones. With a virtual auditory display, a listener perceives the sounds as coming from locations in the external environment, not as emanating from the headphones or inside their own head, as is usually the case when wearing headphones. This sometimes startling effect is possible because virtual audio recreates the physical stimulus in a real-world acoustic environment, in a way that is simply not captured by traditional auditory displays.

Normal auditory spatial perception is accomplished in the brain by making comparisons of the acoustical signals reaching the two ears. Since the ears are separated in space, a given sound wave reaches the two ears at different times (the interaural temporal difference or ITD) and has different intensities (the interaural level difference or

ILD). Therefore, depending on where in space the sound is coming from, the two ears receive different acoustical signals that can be used to locate a sound on the horizontal plane (Wightman & Kistler, 1993). In addition to these binaural cues to horizontal location (azimuth), both monaural and binaural cues can be used to determine the vertical location (elevation) of a sound. Manipulating the vertical elevation of a sound changes the spectral shape reaching the ear canal, due to shadowing and reflections by the pinnae, head, shoulders, and torso (Yost, 2000). So, to *simulate* a spatial sound with headphones, the sounds being played to each ear can be filtered to introduce the ITD, the ILD, and spectral shapes of the desired location.

The ITDs, ILDs, and spectral changes for each location in space can be described empirically using head-related transfer functions (HRTFs). HRTFs are captured by placing microphones in a listener's ear canals or in the ears of a dummy head, then recording flat wideband sounds emanating from a large number of directions within an anechoic chamber. In effect, the pinnae, head, shoulders, torso, etc. act as a filter, changing the flat wideband signals into unique spectral shapes. These resulting spectral shapes take various forms, depending on which direction the sound is coming from. Thus, HRTFs are a description of how sounds are changed as they travel from specific points in space to the entrance of the ear canals (for further discussion of HRTF synthesis, see Wightman & Kistler, 1989a).

To simulate a sound coming from a given direction, the signals for each ear are convolved with the HRTFs to produce the appropriate ITD, ILD, and spectral cues corresponding to that direction. Presenting the modified signals over headphones will re-create, at the eardrums, the sounds that a person would hear if they were actually listening in a real-world environment, and the illusion of sounds coming from particular directions in external space is readily perceptible. This illusion can be extremely compelling (Gilkey & Weisenberger, 1995), and in many cases, virtual sounds are functionally equivalent to free-field sounds (Wightman & Kistler, 1989b).

Previous Research on Aurally-aided Visual Search

As far back as the 1960's, scientists were investigating the use of auditory cues as an aid for visual search tasks in complex operating environments. Mudd and McCormick (1960) asked participants to search a mock control panel filled with 32 dials for a single "deviant" dial that was oriented differently than the rest. Their study did not use 3D auditory cues; instead, pure tones were coded by varying the lateralization, frequency, and duration of the sound to represent the location of the target dial. The lateralization code (sound presented in either the left or right ear) reduced the search area to the left or right half of the panel; the frequency code (500 or 1000 Hz) reduced the search area to the bottom or top of the panel; and the duration code (0.2 or 0.5 s), when coupled with the lateralization code, reduced the search area to the inner or outer portion of the appropriate side.

Mudd and McCormick's results showed that when using only the lateralization cue, participants decreased their search times from an average of 18.15 to 10.49 s. By adding the frequency and duration codes to the auditory signal, search times were reduced even more to 6.21 s. Although these cues were not "spatialized" in the modern sense of being three-dimensional, they still contained information about the spatial location of the stimulus. Thus, these results show that auditory cues with some form of spatial information are effective at improving visual search performance.

More recent research on aurally-aided visual search has studied the effect of spatial (3D) auditory cues on performance. In a typical experiment, a real spatial sound cue is presented with loudspeakers in a *free-field* environment (no obstructing objects or interfering boundaries) or a virtual spatial sound cue is presented over headphones. In both cases, the sound cue is displayed at the same location as the visual target. Generally, average search times when a co-located spatial auditory cue is provided are compared to search times when a non-spatial cue or no cue is provided.

The reported benefits of spatial audio include: significant decreases in visual search times (Bolia et al., 1999; Perrott et al., 1996), improvements in head movement efficiency during search (Nelson, Hettinger, Cunningham, Brickman, Haas, & McKinley, 1998), decreases in the subjective workload of the operator, and increases in situation awareness (McKinley & Ericson, 1995). In addition, manipulations that typically hurt visual search times, such as enlarging the search area (Perrott et al., 1990) or increasing the number of visual distractors (Perrott, Sadralodabai, Saberi, & Strybel, 1991; Bolia et al., 1999), are significantly less detrimental for performance when spatial auditory cues are presented. All of these benefits likely occur because the spatial audio provides an intuitive and easily-perceived cue that contains location or direction information. Thus, the area that an observer needs to search can be greatly reduced by providing spatial auditory cues, making the act of searching significantly faster and easier.

Reductions in Search Times. Perhaps the most important and robust finding in the aurally-aided visual search literature is the large reduction in response times when 3D audio cues are displayed. In an early study examining the effect of 3D audio on visual search, Perrott et al. (1990) asked participants to search for and identify a visual target.

One search condition presented an audio cue from a speaker placed directly ahead (at the fixation point) on every trial, regardless of where the visual target was located; thus, the audio cue was not spatially correlated with the target. The other condition presented an audio cue from a speaker at the same location as the visual target; in this condition, the audio cue was spatially correlated with the target. Visual search times were found to be significantly faster with spatially correlated auditory cues than with uncorrelated cues. At the most difficult search locations (elevated sounds coming from behind), response times were reduced from about 2600 ms to about 1300 ms, a reduction of approximately 50%. Other studies have found similar significant reductions in response times when spatial auditory cues were provided (Perrott et al., 1991; Perrott et al., 1996; Bronkhorst, Veltman, & van Breda, 1996; Flanagan, McAnally, Martin, Meehan, & Oldfield, 1998; Bolia et al., 1999).

Improvements in Detection Performance and Subjective Measures. In addition to the typical response time measures, Nelson et al. (1998) investigated aurally-aided visual search performance in terms of detection efficiency, perceived workload, and head movement efficiency. Their task required observers to locate a steadily approaching target aircraft in a simulated environment presented either on an external dome display or within a helmet-mounted display (HMD). The four conditions of their experiment were: the presence of 3D audio cues (azimuth, elevation, and range), 2D audio (azimuth and elevation), non-spatialized audio, and no audio. Detection efficiency was measured with two metrics: the percentage of visual targets detected and the simulated distance at which targets were detected (since the target approached at a constant rate, the distance of detection metric is essentially reciprocal to response times). The perceived mental workload was measured by administering a brief questionnaire (the NASA Task Load Index) after each block of trials. Head movement efficiency was measured using a head-tracking system that recorded the total angular head displacements and average head velocity during the search tasks. The localized auditory conditions (2D and 3D) resulted in the best metrics, including the highest target detection efficiencies (the highest percentage of detections and the farthest distances at which targets were detected), the lowest workload ratings, and the most efficient head movements (the smallest total angular head displacements and the smallest average head velocities).

In an effort to examine the feasibility of implementing a virtual audio cuing system in an actual operating environment, McKinley and Ericson (1995) performed a flight demonstration with a 3D audio display. The task required pilots to visually locate and then verbally identify ground targets (e.g., a tower or a bunker) during flight. Virtual audio cues were presented over a head-set integrated within the pilots' flight helmets. A head-tracking system ensured that the perceived spatial location of the auditory cue remained correlated with the actual spatial location of the target, no matter where the pilots' heads happened to be pointing. No quantitative data were recorded from the flight demonstration. However, the pilots reported that targets were acquired faster with the 3D audio system than with the traditional visual heads-up display (HUD) and that their workload was decreased. In addition, the pilots felt that the 3D audio display offered an increase in situational awareness.

The Eccentricity Effect. Research on visual search has consistently shown an effect of the location of the target on response times, or the target's *eccentricity* from the initial line of gaze. This finding does not seem surprising if we consider that targets appearing farther away from the fixation point require that a larger area be searched until the target is found, which will generally increase search times, or when we consider that moving one’s eyes 80 degrees takes longer than moving 40 degrees. Interestingly, when a 3D audio cue is provided, this effect of eccentricity is sometimes reduced or even eliminated; visual search times for a target far in the periphery can sometimes be just as fast as search for a target near the initial line of gaze (Perrott et al., 1990). This also means that the benefit provided by 3D audio (relative to no audio cues) increases as the as the effective search area grows larger (or as the eccentricity of the target increases).

The eccentricity of the target locations was an additional independent variable in the work of Perrott et al. (1990), whose experimental design was discussed earlier. Targets appeared at various locations within a search field spanning 260 degrees horizontally and 92 degrees vertically. They found that the advantage of spatialized audio was more apparent at the farther eccentricities (a benefit of approximately 50%), when the effective search areas were especially large. The smallest reduction in response times (approximately 15%) was found when the target was within the central visual field (within 10 degrees of the initial line of gaze). Although this reduction was relatively small, the fact that search times were reduced at all within the central visual field was unexpected and impressive, considering that observers were looking almost directly at the targets at the start of the trials.

In a similar series of experiments, Perrott et al. (1991) examined aurally-aided search times to compare performance with unaided search. Again, eccentricity of the target was manipulated and could appear anywhere within a 30 degree search field, directly ahead. Participants were required to locate and then identify a target as being one of two alternatives. In the no-sound condition, there was no audio cue. In the spatially-correlated condition, a speaker presented an audio cue at the same location as the visual target. Again, the largest improvements in search times with 3D audio were at the farthest eccentricities (at 14.8 degrees from the fixation cross in the most difficult search condition, response times were reduced by approximately 30%). Also, they were able to replicate their earlier work in Perrott et al. (1990), which showed a beneficial effect of 3D audio even within the central visual field.

The Visual Load Effect. Another common experimental manipulation in traditional visual search tasks is the addition of distracting visual stimuli. These visual distractors often look similar to the target and their presence makes the target difficult to find. This increase in the *visual load* or *display size* usually translates into longer response times; as more distractors are added, search times get longer. As was found with the eccentricity effect, the addition of 3D auditory cues can reduce or eliminate the effect of visual load on a search task. Similarly, the benefits of 3D audio over unaided search become especially apparent as the visual load increases.

In addition to varying the eccentricity of the targets, Perrott et al. (1991) also varied the number of visual distractors that appeared from 0 to 63. The visual distractors looked similar to the target and were intended to control the difficulty of the task. The results suggested that as the number of visual distractors increased, the benefit of 3D audio also increased. For instance, when there were no distracting stimuli, free-field audio cues improved search times by only 8% relative to the no-sound condition. However, when large numbers of distractors were present (63), search times were improved by 28 % with a free-field audio cue.

Bolia et al. (1999) also manipulated the number of visual distractors, using 1, 5, 10, 25, or 50 distractors. They asked participants to find a visual target that could appear within a search field of 360 degrees horizontally by 160 degrees vertically. The targets were a set of either 2 or 4 closely spaced LED lights; the distractors were very similar sets of either 1 or 3 LEDs. The three main conditions of their experiment were: no audio cues, virtual audio cues (presented over headphones), and free-field audio cues (presented with loudspeakers). The task, without audio cues, was very difficult when visual distractors were present. For instance, when there were 50 visual distractors, average unaided search times were almost 15 seconds. When a virtual audio cue was displayed in the presence of 50 distractors, search times dropped to less than 4 seconds (an improvement of 73%). When a free-field sound cue was displayed, search times were about 1 second (a dramatic improvement of 93%), regardless of the number of distractors. These findings show that when a 3D audio cue is added to a visual search task, the effect of visual distractors is reduced considerably (with virtual audio), and may even be eliminated (with free-field audio), at least for difficult or complex searches.

The Present Research Question

The literature on aurally-aided visual search suggests that there are many significant performance advantages compared to unaided search under a variety of experimental manipulations. However, most of this literature consists of searches for static (non-moving) targets hidden among static distracting stimuli. No research has apparently examined aurally-aided visual search performance in an environment with dynamic (moving) stimuli. Researchers have recommended that future research should assess “the effects of virtual localized auditory cues on visual detection tasks that involve multiple targets, visual distractors, and *non-stationary targets* [italics added]" (Nelson et al., 1998, p. 459). This last aspect of visual searching may be especially important since in most real-world situations the observer and/or the stimuli are in motion. The goal of the present research is to assess how 3D auditory cuing affects visual search performance when considering dynamic stimuli.

As discussed earlier, traditional visual search tasks become more difficult with the enlargement of the effective search area (the *eccentricity effect*; see Perrott et al., 1990) or the addition of multiple visual distractors (the *visual load effect*; see Perrott et al., 1991; Bolia et al., 1999). Moreover, it is in these most difficult search conditions when 3D audio cues provide the largest advantages over unaided search. We expect that moving stimuli will also increase the difficulty of an unaided visual search task since dynamic visual acuity is generally poorer than static acuity (Morrison, 1980), and thus we expect a larger advantage of 3D audio cues.

There is some experimental evidence suggesting that dynamic visual search is indeed more difficult than static search. Erickson (1964) found that fast moving targets were harder to detect than slower ones in a visual search task. Erickson's task required participants to find Landolt C targets hidden among a background of similar-looking rings in a vertically moving field (all stimuli moved in the same direction at the same speed: either 5, 7, or 10 deg/s). His results showed that detection performance markedly decreased as velocity increased. With 48 visual distractors, about 67% of the targets were detected in a field moving at 5 deg/s. When the velocity was doubled to 10 deg/s, performance dropped to a detection-rate of about 47%. These considerations suggest that dynamic search is more difficult than static search; thus, we expect to find that 3D audio offers a greater overall benefit in dynamic search environments than in static environments.

However, it remains possible that the benefit of 3D auditory cues in a dynamic environment will be poorer than a static environment. Previous research on auditory localization suggests that spatial acuity is better for static sounds than moving sounds. Under ideal laboratory conditions, the minimum audible angle (MAA) for static sounds is about 1 degree of arc; in contrast, the best minimum audible movement angle (MAMA) for dynamic sounds is about 2 to 5 degrees (Grantham, 1994). Therefore, it is possible that the less accurate localization cues for moving sounds will limit the usefulness of 3D audio in a dynamic environment relative to a static environment.

The present study was undertaken to resolve this issue by answering this question: how does visual search performance in a static environment compare to a dynamic environment when 3D auditory cues are given? Results should aid in attempts to increase search performance and spatial situational awareness for cockpit and motor-vehicle applications. Specifically, these applications could include: an auditory display for threat warning location, aircraft wingman location, collision avoidance, spatial communications separation, air and ground target location, and navigation aids (McKinley & Ericson, 1995). Other possible technological and research applications include cuing teleoperators on the locations of targets or obstacles and attentional cuing for operators using control panels and visual displays in command and control environments.

II. METHOD

The experimental setup was similar to a traditional visual search task and the main dependent variable of interest was response time. Our goal was to discover how visual search performance in a dynamic environment compares to a static environment when 3D auditory cues are displayed. The experiment was conducted in the Aerospace Vision Experimental Laboratory (AVXL) at the Air Force Research Laboratory located at Wright-Patterson Air Force Base, Ohio.

Participants

The 8 participants reported having normal or corrected-to-normal visual acuity and normal hearing. They ranged in age from 23 to 43 years old. Four of them had participated in the pilot study that preceded this research; one of these was the author. The four other participants did not have previous experience with the task. The total time requirement for each participant was 5 hours (which was generally spread out over 5 separate days, 1 hour per day). The participants were not paid.

Apparatus

The visual stimuli were displayed on a screen by an overhead projector that produced a 1024 x 768 resolution image with a refresh rate of 75 Hz. Participants were seated 75.5 inches from the screen so that the projected images spanned 60° horizontally and 47° vertically. The projected image was centered horizontally with the observer, but was vertically raised about 12.5 inches (or about 9 degrees of visual angle) above the observer's horizontal line-of-gaze (see Figure 1).

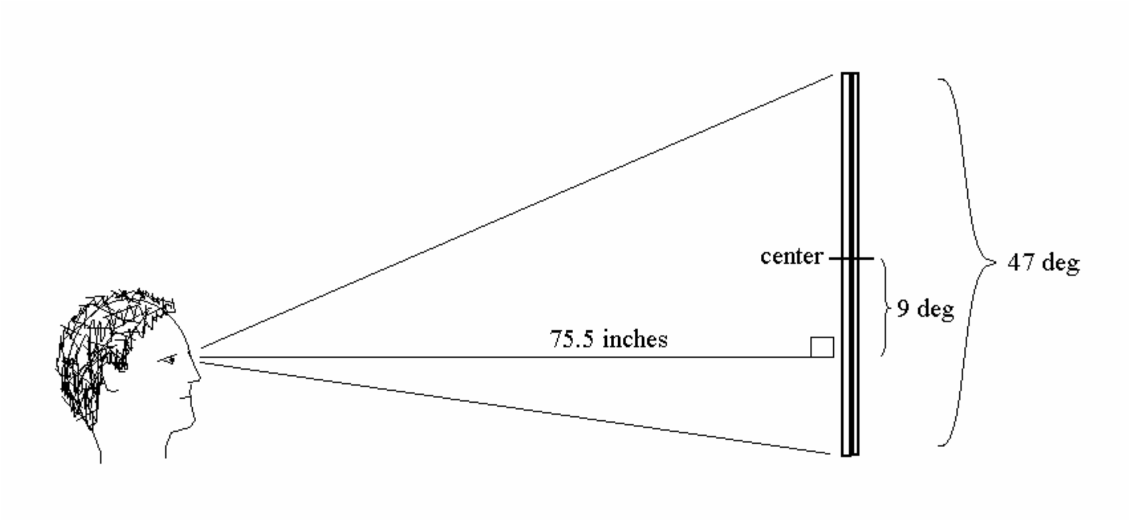


Figure 1. The visual display experimental set-up. The projected image spanned 47 degrees of vertical visual angle, and the center of the image was about 9 degrees above the participants' horizontal line-of-gaze. Participants were seated with their heads 75.5 inches away from the display.

In the 3D audio conditions, participants' head positions were monitored by a 3rdTechTM HiBall-3100 Wide Area Tracker, an optical head-tracking system with a temporal resolution of 1500 – 2000 Hz and an orientation resolution of 0.01 degrees RMS (3rdTech, Inc., 2006). When coupled with a computer and headphones, the head-tracking system ensured that when an auditory cue was presented, it would always be spatially correlated with the visual target, regardless of where their head was pointed. The auditory stimuli were presented with Sennheiser HD 260 Pro headphones, which had the head-tracker mounted on top.

Stimuli

Visual. The visual stimuli (one target and 15 distractors) were black rings on a white background. Each of the rings spanned 0.96 degrees of visual angle. The target was identical to the distractor rings except for a small gap introduced on either the left or the right side. The size of the gap in the target ring was 0.12 degrees of visual angle (see Figure 2). This gap size was chosen so that participants could not identify the target using peripheral vision; instead, they were required to visually scan the display until the target became foveated. Pilot studies revealed that the selected target gap size became very difficult to detect at about 5 to 10 degrees of retinal eccentricity.

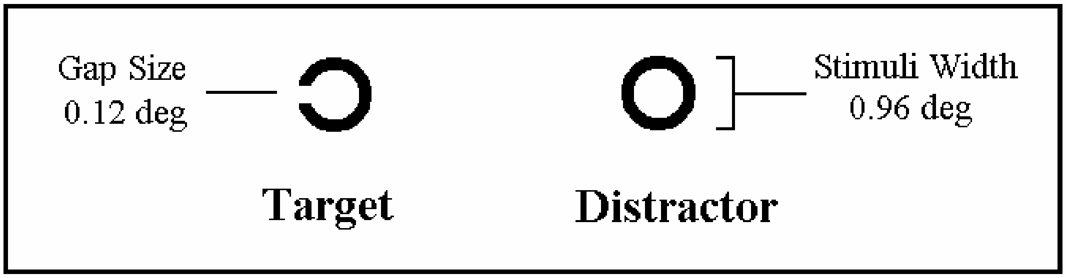


Figure 2. The visual stimuli. The gap size of the target spanned 0.12 degrees of visual angle, and the width (diameter) of both the targets and distractors was 0.96 degrees of visual angle.

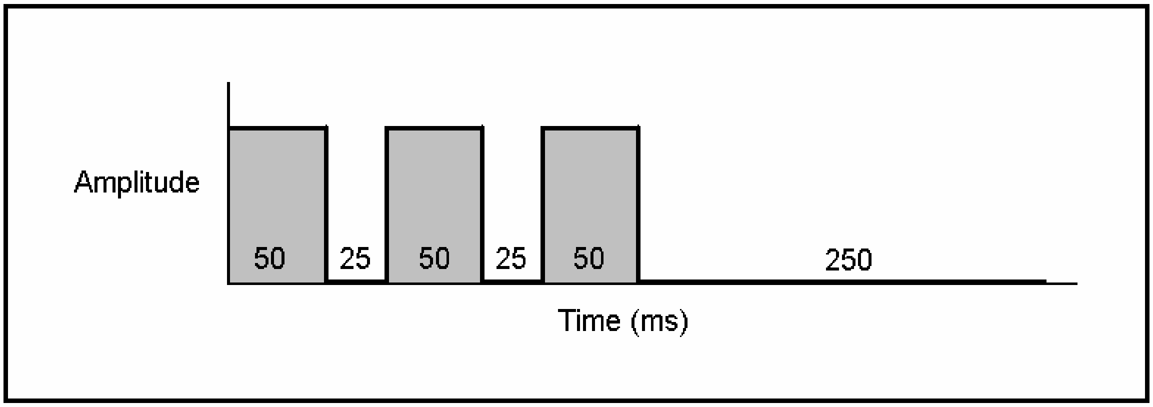


Figure 3. Temporal profile of the auditory cue. The 50-ms bursts of white noise were separated by 25-ms gaps of silence. The last burst was followed by 250 ms of silence. The length of each cue was 450 ms.

Auditory. The sound cue consisted of three consecutive 50-ms bursts of wideband white noise separated by 25-ms gaps of silence, and followed by 250 ms of silence (see Figure 3). The sample rate was 44,100 samples/s. The cue was repeated continuously during each trial in the auditory conditions, and was presented at a comfortable listening level.

For each audio trial, the sound cue was filtered with a generic set of HRTFs and displayed using NASA's "sound lab" software (SLAB, Version 5.7.0; also see Miller & Wenzel, 2002). It should be noted that the "generic" HRTFs were recorded from an individual who was not a participant in the study. To combat the problems of low-frequency fidelity in experimentally measured HRTFs, a "snowman" model (which assumes a perfectly spherical head sitting atop a perfectly spherical torso) was used to correct the low-frequency component of the recorded HRTFs (see Algazi, Duda, & Thompson, 2002).

Procedure

The experiment was a visual search task using a two-alternative forced-choice (2AFC) design. Before beginning, participants were instructed to visually locate the target ring and then identify whether the gap was located on the left or the right side of the target. Participants donned headphones (with the head-tracker mounted on top) and sat facing the display screen in a dimly lit room. They were required to gaze at a fixation cross before each trial began. When ready, they pressed a button to start the trial. When the 'start' button was pressed, the fixation cross disappeared, a timer started, and the 16 stimuli were presented (one target and 15 distractors). Participants had to visually search the display, find the target, and then indicate on which side of the target the gap was located by pressing either the 'Left' or 'Right' button on a wireless keypad (see Figure 4). When the 'Left' or 'Right' button was pressed, the timer was stopped and their responses and response times were recorded. The screen was then cleared and the fixation cross for the next trial was displayed. The trials were entirely self-paced. Participants were instructed that both accuracy and speed were important.

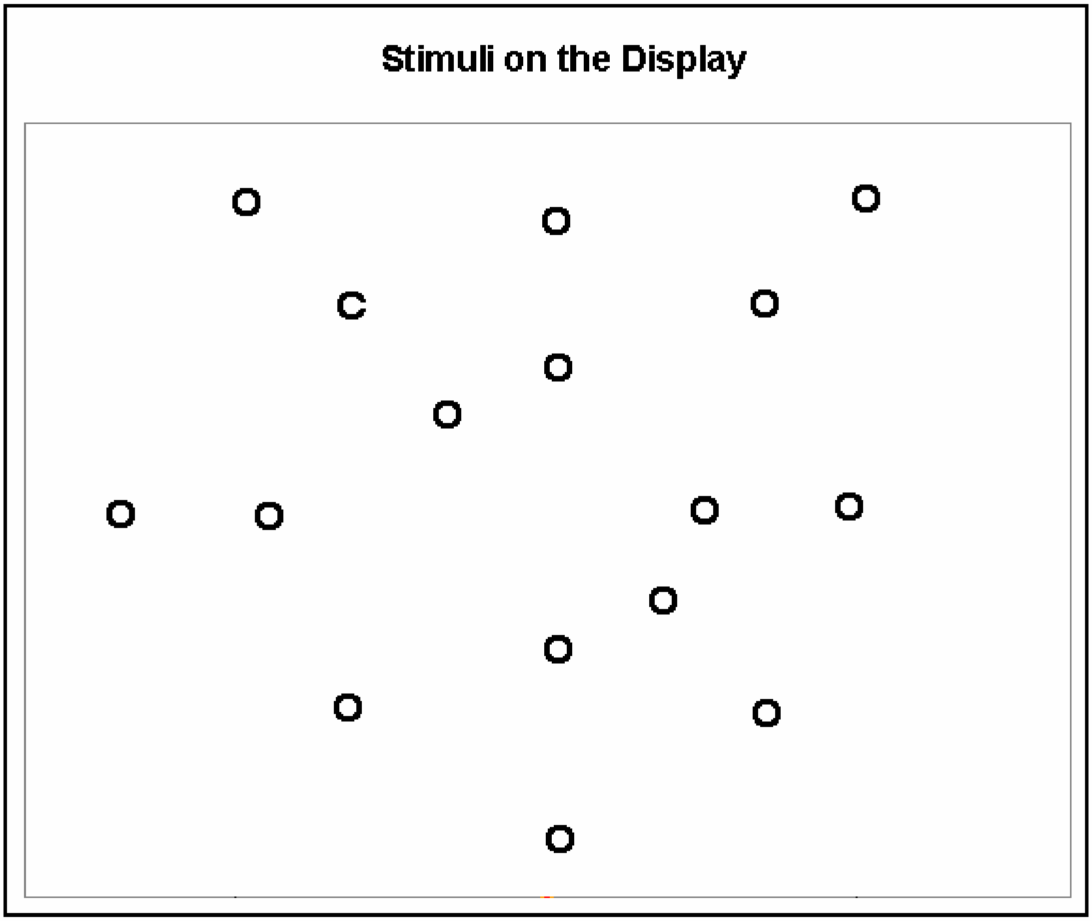


Figure 4. An example of the search task for the target among 15 distracting rings. In this case, the participant should indicate that the gap is located on the right side of the target.

The four conditions of the experiment were: (1) a static environment with no audio cues, (2) a static environment with 3D audio cues, (3) a dynamic environment with no audio cues, and (4) a dynamic environment with 3D audio cues. A single block (condition) contained 176 trials (22 locations x 8 repetitions per location). Each session, which consisted of four blocks, contained 704 trials (4 blocks x 176 trials). In addition, each participant viewed four experimental sessions. Consequently, each participant ran in

2,816 trials (4 sessions x 704 trials). In totality, the experiment recorded 22,528 trials: 8 (subjects) x 4 (blocks) x 4 (sessions) x 22 (locations) x 8 (repetitions).

Static Conditions. In the static conditions, the stimuli were presented at 16 of 22 possible locations that were 9, 18, or 27 degrees away from the fixation cross. There were 8 possible locations at 9 degrees, 8 at 18 degrees, and 6 at 27 degrees (see Figure 5). Within each condition, the target ring appeared at all 22 starting locations (22 positions x 8 repetitions = 176 trials per block). The distractor rings randomly appeared at 15 of the remaining locations.

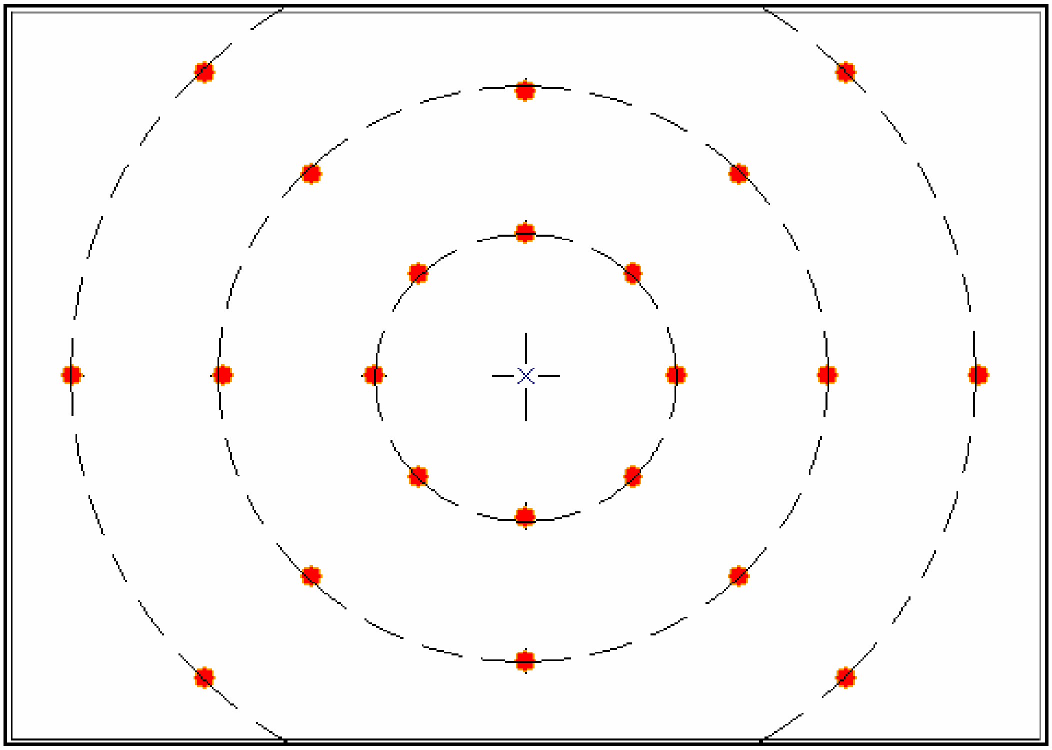


Figure 5. The 22 possible target starting locations at 9, 18, and 27 degrees from the fixation cross.

Dynamic Conditions. Again, the stimuli started at 16 of the 22 possible locations that were 9, 18, or 27 degrees away from the fixation cross. However, in the dynamic conditions, all of the stimuli immediately began moving at a speed of 10 degrees of visual angle per second. For each trial, the 16 visual stimuli were randomly assigned one of 8 possible trajectories that included the four cardinal directions (Up, Down, Left, Right) and the 45° oblique directions between them (see Figure 6). Each direction of movement was assigned to only 2 stimuli for each trial. Within each block, the target ring moved on all 8 trajectories starting at each of the 22 possible starting locations (22 locations x 8 trajectories = 176 trials per block). The distractor rings randomly appeared at 15 of the remaining starting locations and were not able to occlude the target ring at any time during their movement. Stimuli were not permitted to move off of the display screen; if a ring reached the edge, it "bounced" off the edge of the image using realistic physics and stayed within the display area.

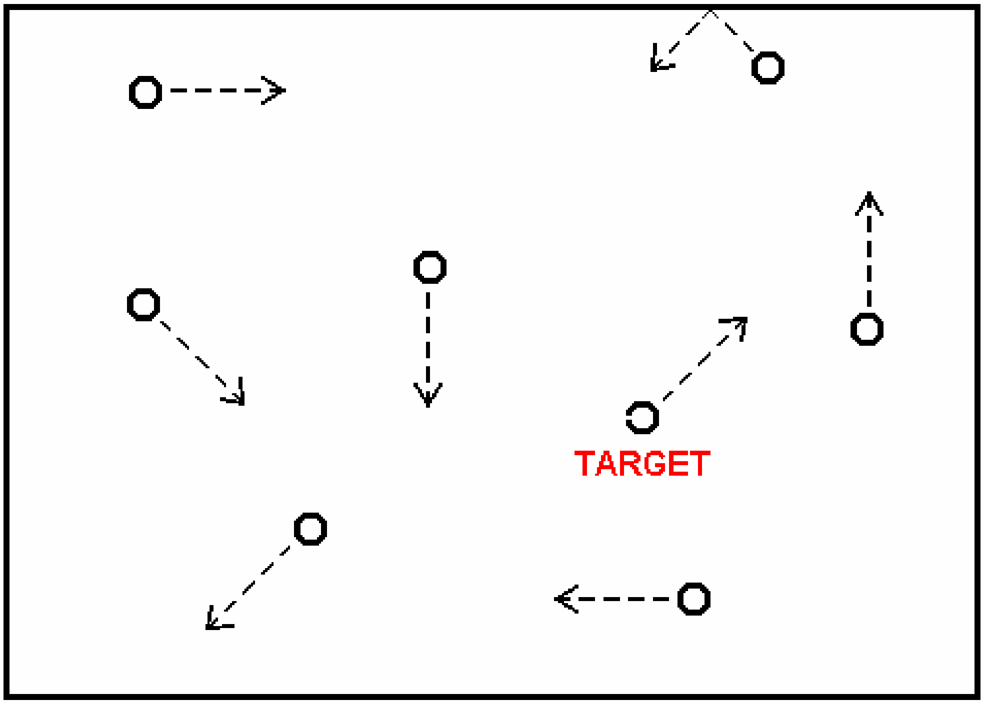


Figure 6. An example of the target and 7 distractor rings in the dynamic condition, each moving in one of the eight possible directions at 10 deg/s. Rings "bounced" off the edge of the image using realistic physics to stay within the display area.

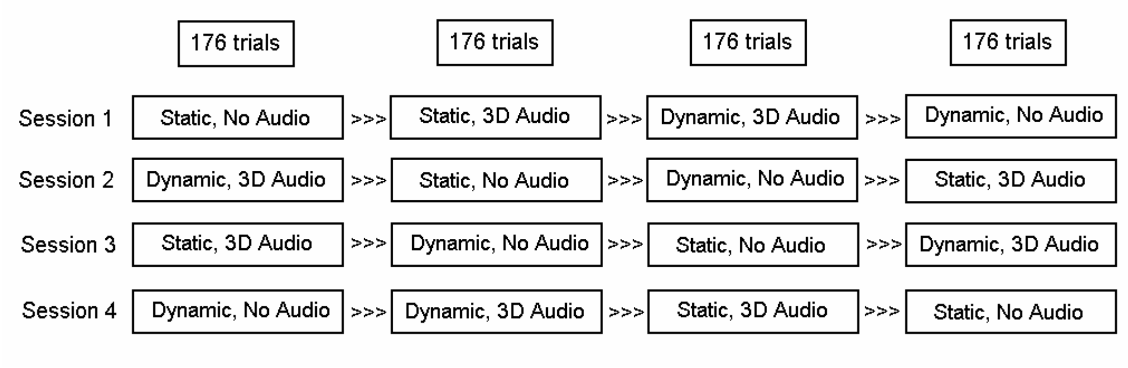
No Audio Conditions. In the no-audio conditions, no auditory cues were presented. The bulkiness of the headphones could have affected head movements (and thus search performance), so participants were still required to wear the headphones. This requirement ensured that the 3D audio manipulation was not confounded with the presence or absence of head gear.

3D Audio Conditions. In the 3D audio conditions, auditory cues were presented to the participants over the headphones. When the participant pressed the 'start' button and the visual stimuli were displayed, the 3D auditory cue (three bursts of white noise) immediately sounded and repeated until the end of the trial. The virtual location of the auditory cue was at the same spatial location as the visual target. When the participant signaled the location of the target gap by pressing the appropriate button (Left or Right), the visual display was removed and the auditory cue immediately stopped. The head-tracking system ensured that the audio cue and visual target were always co-located regardless of where the participant's head was pointing, even when the target was moving in the dynamic conditions.

Design

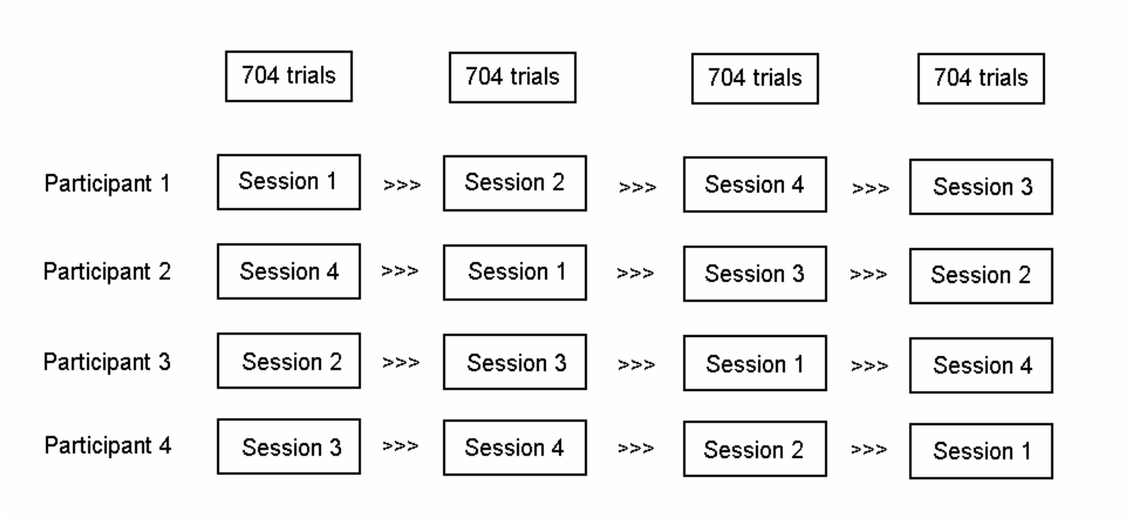
The presentation order of the blocks was counter-balanced across sessions with a balanced Latin Square design: each block occurred in every ordinal position exactly once and no block preceded or followed another more than once (see Figure 7). In addition, the presentation order of the sessions was also counter-balanced across participants with a balanced Latin Square (see Figure 8).

Training. Every participant was given a training session before collecting data. The training session consisted of 150 trials from each of the four conditions, for a total of



	176 trials	176 trials	176 trials	176 trials
Session 1	Static, No Audio >>>	Static, 3D Audio >>>	Dynamic, 3D Audio >>>	Dynamic, No Audio
Session 2	Dynamic, 3D Audio >>>	Static, No Audio >>>	Dynamic, No Audio >>>	Static, 3D Audio
Session 3	Static, 3D Audio >>>	Dynamic, No Audio >>>	Static, No Audio >>>	Dynamic, 3D Audio
Session 4	Dynamic, No Audio >>>	Dynamic, 3D Audio >>>	Static, 3D Audio >>>	Static, No Audio

Figure 7. The experimental design for a single participant. The presentation order of the blocks was counter-balanced across sessions via a balanced Latin Square design.



	704 trials	704 trials	704 trials	704 trials
Participant 1	Session 1 >>>	Session 2 >>>	Session 4 >>>	Session 3
Participant 2	Session 4 >>>	Session 1 >>>	Session 3 >>>	Session 2
Participant 3	Session 2 >>>	Session 3 >>>	Session 1 >>>	Session 4
Participant 4	Session 3 >>>	Session 4 >>>	Session 2 >>>	Session 1

Figure 8. The experimental design for four participants. The presentation order of the sessions was counter-balanced across participants via a balanced Latin Square design.

600 training trials. The order of the training conditions was structured so that the participant started under the simplest condition, and the additional conditions added various levels of complexity to the task. The order of conditions for the training session was: Static with No Audio, Dynamic with No Audio, Static with 3D Audio, and Dynamic with 3D Audio. Participants were instructed to use the training session as an exploratory experience to gain comfort pressing the appropriate buttons, viewing the stimuli, and

correctly using the 3D audio as a cue to the target. After completing the first four blocks with 50 trials in each block, the same procedure was repeated twice so that every participant viewed each condition three times (150 trials per condition) and experienced a total of 600 trials. Feedback as to the accuracy of responses and average response times was given at the end of the training blocks; no feedback was provided during the trials.

For data collection sessions, each block of the experiment was preceded by a 50-trial "warm-up" block containing only the condition for the following block. For instance, before beginning data collection on the "Static, No Audio" condition, participants practiced on 50 "warm-up" trials containing no motion and no auditory cues. Again, feedback as to the accuracy of responses and average response times was given at the end of the training blocks; no feedback was provided during the trials.

Time requirement. Participants were given short breaks between each block. In addition, the trials were self-paced, allowing participants to pause at any time between trials. The total time requirement for each participant was no more than five hours (one training session plus four experimental sessions, each taking at most an hour to complete), spread over five days with one session per day.

III. RESULTS AND DISCUSSION

The main variables of interest in this experiment were the type of visual environment (static or dynamic), the presence or absence of an auditory cue, target eccentricity, session, direction of target motion, and the target starting location. All of the independent variables were treated as fixed within-subjects effects in a repeated-measures analysis of variance (ANOVA). Incorrect as well as premature responses (response times less than 100 ms) were excluded from analysis (1.2% of trials). Post-hoc analyses were predominantly conducted with Games-Howell's (*GH)* tests, which controlled for unequal sample sizes and heterogeneous variances. All tests of significance were conducted with an alpha level of 0.05.

Since reaction time distributions are nearly always positively skewed, researchers often transform their data to normalize the distributions before performing statistical tests such as ANOVA (e.g., Flanagan, McAnally, Martin, Meehan, & Oldfield, 1998). In keeping with this practice, we log-transformed the data before ANOVAs were performed (for further discussion of reaction time distribution analysis, see Ratcliff, 1993). Figure 9 shows the frequency histogram for the raw response time data, before a logarithmic transformation; it is highly skewed in a positive direction. Figure 10 shows the frequency histogram for the log-transformed response time data; notice that it is a better approximation of a normal distribution and the skewing is greatly reduced.

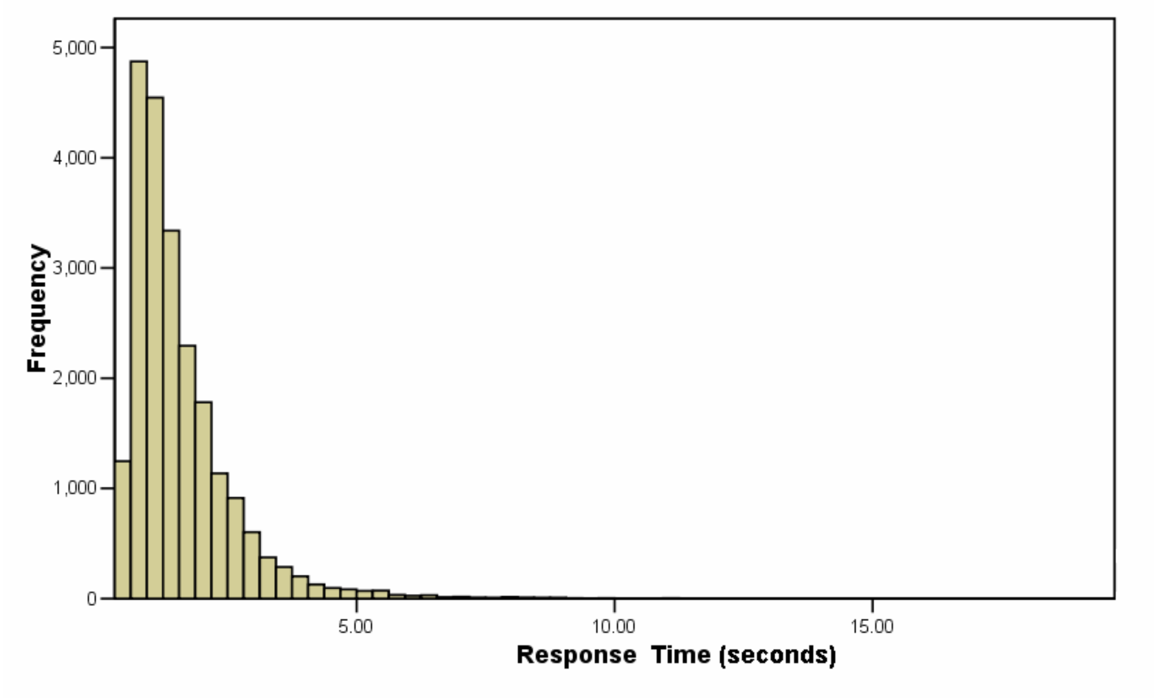


Figure 9. Frequency histogram of the raw response time data, before the logarithmic transformation. Notice that it is highly positively skewed and non-normal.

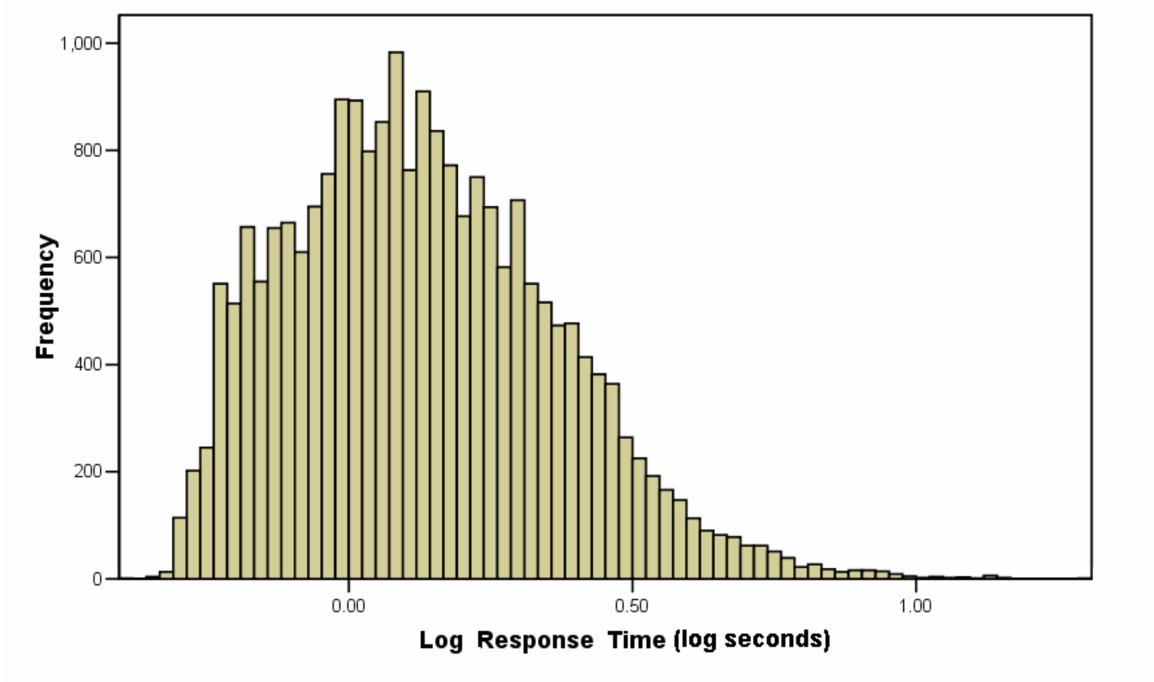


Figure 10. Frequency histogram of the logarithmically-transformed response time data. Note that it is only slightly skewed and is a better approximation to a normal distribution.

All of the statistical tests were performed on the logarithmically-transformed data. However, for ease of discussion, the means of the untransformed response times are reported in the text and shown graphically.

Analysis of Violations of Sphericity

Repeated measures ANOVA requires that the data are *spherical*, meaning that the variances of the differences between pairs of treatment levels are roughly equal (Field, 1998). When there is a violation of sphericity, the critical *F*-ratios obtained from ANOVA tables are generally too small, increasing the probability of committing a Type I error (rejecting a true null hypothesis). To deal with sphericity violations, corrections can be applied that adjust the degrees of freedom in the ANOVA test in order to produce a more accurate significance level, such as the Greenhouse-Geisser or Huynh-Feldt corrections (Baguley, 2004). However, May, Masson, and Hunter (1990) note that when the obtained *F*-ratios are much larger than the tabled critical values, rejection of the null hypothesis is still valid even without performing corrections. All of our significant overall effects had very large *F*-ratios, with corresponding *p*-values of 0.001 or less. In fact, the overall analysis came to the same conclusions as all three of the adjusted *F*-tests provided by SPSS (the Greenhouse-Geisser, Huynh-Feldt, and Lower-bound sphericity corrections) in terms of which effects were significant, and the *p*-values were not noticeably altered by the corrections. Therefore, all of the reported *F*-tests are uncorrected.

Percent Correct Analysis

All of the observers performed extremely well. Only 270 (or 1.2%) of the 22,528 total trials had to be excluded due to incorrect responses (1.1%) or premature responses

(0.1%). The largest error rate for a single observer was only 2.4%. While 3D auditory cues produced twice the number of errors as did no auditory cues (1.6% versus 0.8%, respectively), the difference of 0.8% was too small to be considered meaningful. Since error rates were so low, no further analyses were conducted on the percent correct data.

Overall RT Analysis

In our overall analysis, response times were the dependent variable. The independent variables under investigation were environment, auditory cue, eccentricity, and session. The direction of motion was not included in this analysis because only half of the trials contained motion, and the target starting location was not included because it was confounded with eccentricity. In this analysis, all main effects were found to be significant, and the two-way interactions of environment by eccentricity and audio by eccentricity were also significant. All other interactions were non-significant. A complete ANOVA table is presented in Appendix A.

Environment. The presence of moving stimuli in the dynamic environment caused an average increase in search times of 470 ms over the static environment (from 1.35 to 1.82 seconds), as shown in Figure 11. This main effect was statistically significant, F(1,7) = 330.654, $p < 0.001$. As previous research on dynamic visual perception has suggested (e.g., Morrison, 1980; Erickson, 1964), the task of finding and identifying a moving target was very difficult, adding almost a half of a second on average compared to the static task.

Auditory Cues. The presence of 3D auditory cues caused a large and significant reduction in search times. As shown in Figure 12, the presence of 3D audio reduced overall search times by 430 ms (from 1.80 s to 1.37 s), an improvement of 24%, which

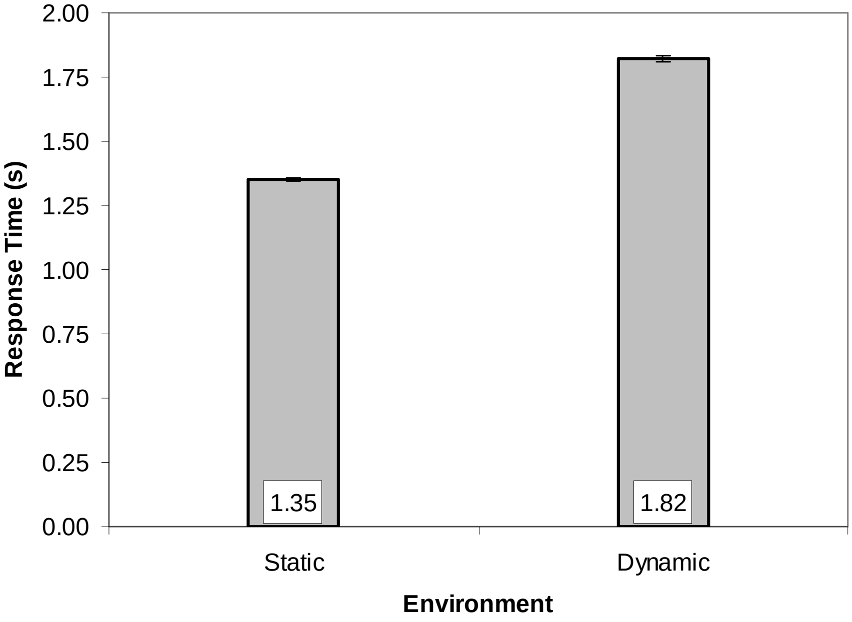


Figure 11. The effect of environment on mean response times. The column labels include mean response times, and the error bars represent ±1 standard error of the mean.

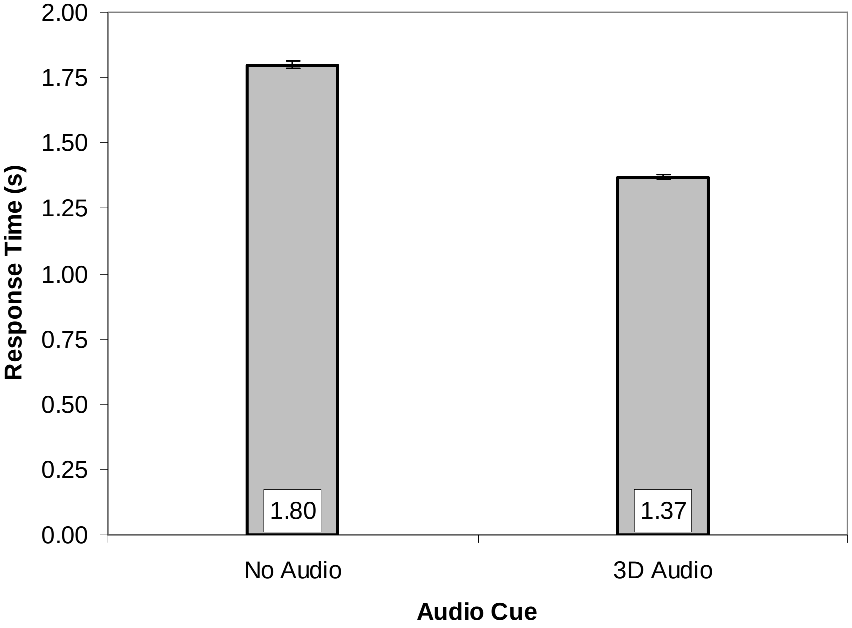


Figure 12. The effect of auditory cues on mean response times. The column labels include mean response times, and the error bars represent ±1 standard error of the mean.

was significant, F(1,7) = 97.595, $p < 0.001$. However, as this main effect was found across static and dynamic conditions, the more interesting results concerning 3D audio can be found by examining its effect within each search environment.

The presence of 3D audio cues improved performance in both static and dynamic environments, as is evident in Figure 13. In the static environment, 3D audio reduced search times by 340 ms (from 1.52 s to 1.18 s), an improvement of 22%. This result supports previous research showing that auditory cues are effective at reducing visual search times in static environments when compared with unaided searches (e.g., Perrott et al., 1996; Bolia et al., 1999). In the dynamic environment, search times were reduced by

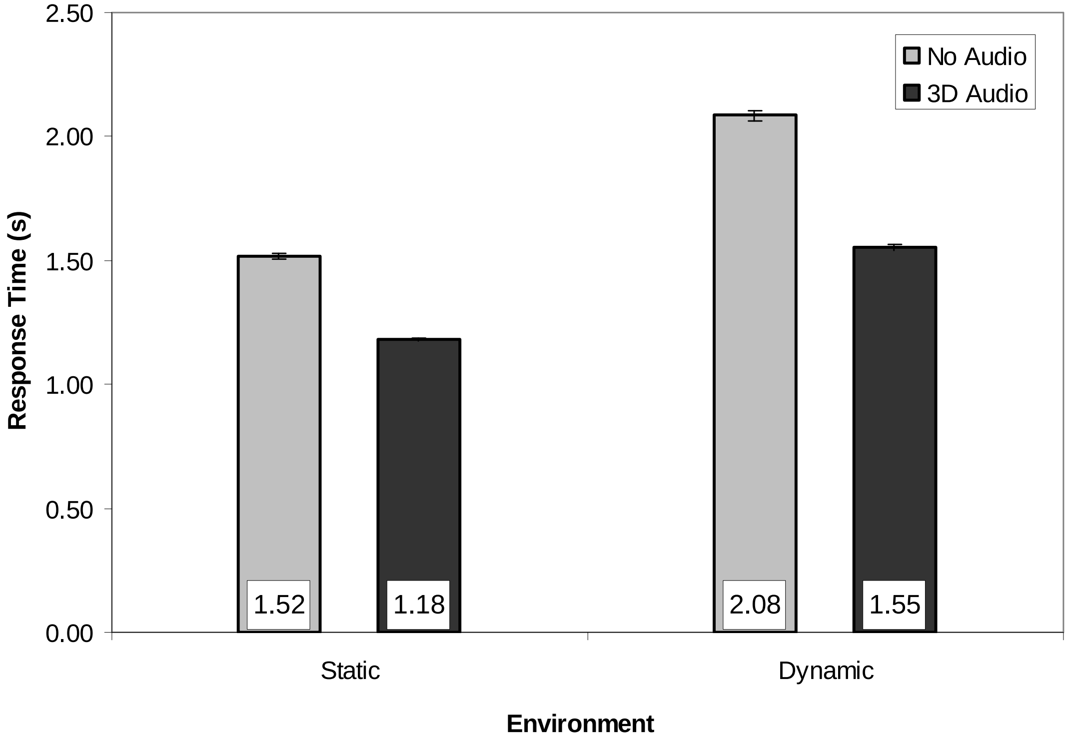


Figure 13. The effects of environment and auditory cues on mean response times. The column labels include mean response times, and the error bars represent ±1 standard error of the mean.

530 ms (from 2.08 s to 1.55 s), a comparable improvement of 25%. It should be noted that there was *not* a significant interaction between environment and auditory cues in this overall analysis. Thus, across participants, 3D audio provided a similar performance benefit in both static and dynamic environments.

Eccentricity. There was a significant main effect of target eccentricity on response times, F(2,14) = 153.823, $p < 0.001$. As shown in Figure 14, overall response times increased as the target eccentricity increased. Post-hoc tests using the *GH* test revealed

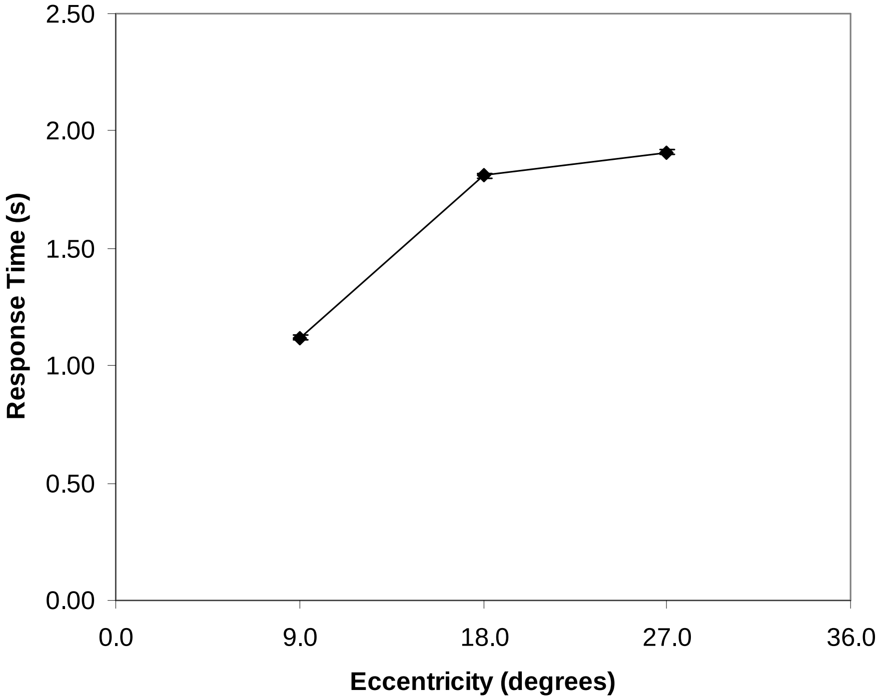


Figure 14. The effect of eccentricity on mean response times. The error bars represent ±1 standard error of the mean and are smaller than the symbols.

significant pairwise differences (alpha = 0.05) between all levels of eccentricity (9, 18, and 27 degrees). Full results of the eccentricity post-hoc tests are shown in Appendix B. Again, as this main effect was found across static and dynamic conditions, the more interesting results concerning eccentricity can be found by examining its effect within each search environment.

The interaction of eccentricity and environment, shown in Figure 15, was significant, F(2,14) = 42.143, *p* < 0.001. A pattern of results similar to the main effect was found in both static and dynamic environments; as target eccentricity increased, response times tended to increase. Thus, in the static condition, our finding of an eccentricity effect confirms previous research (Perrott et al., 1990; 1991). For both the static and dynamic conditions, post-hoc tests revealed significant pairwise differences between all three levels of eccentricity (see Appendix B).

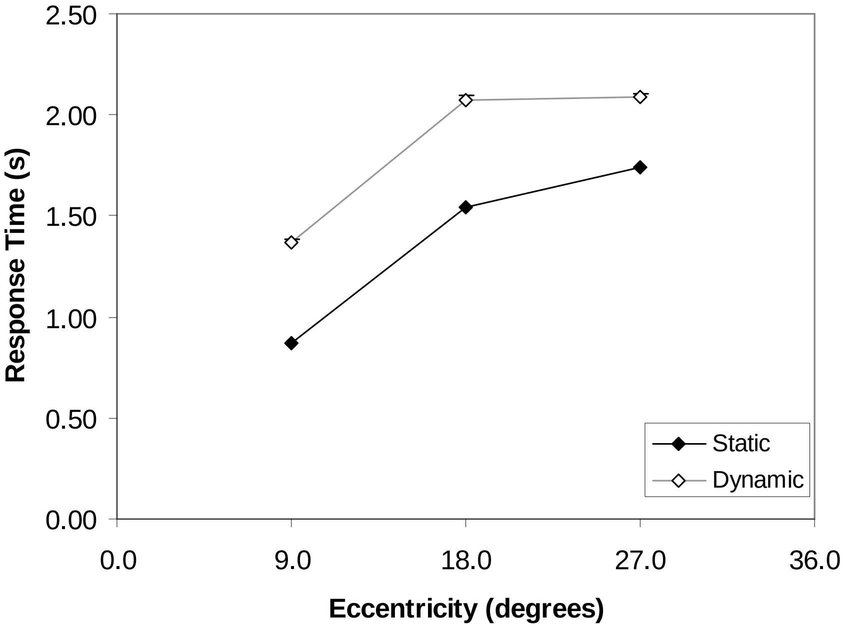


Figure 15. The effects of eccentricity and environment on mean response times. The error bars represent ±1 standard error of the mean and are smaller than the symbols.

The interaction of eccentricity and auditory cue, shown in Figure 16, was also significant, F(2,14) = 96.822, *p* < 0.001. Notice that the benefit provided by 3D audio (the difference between response times in the no audio and 3D audio conditions) increased as the eccentricity increased. Notice also that at 9 degrees of eccentricity, 3D audio reduced search times by 120 ms (10%), despite the fact that observers were practically staring directly at the target at the start of the trial.

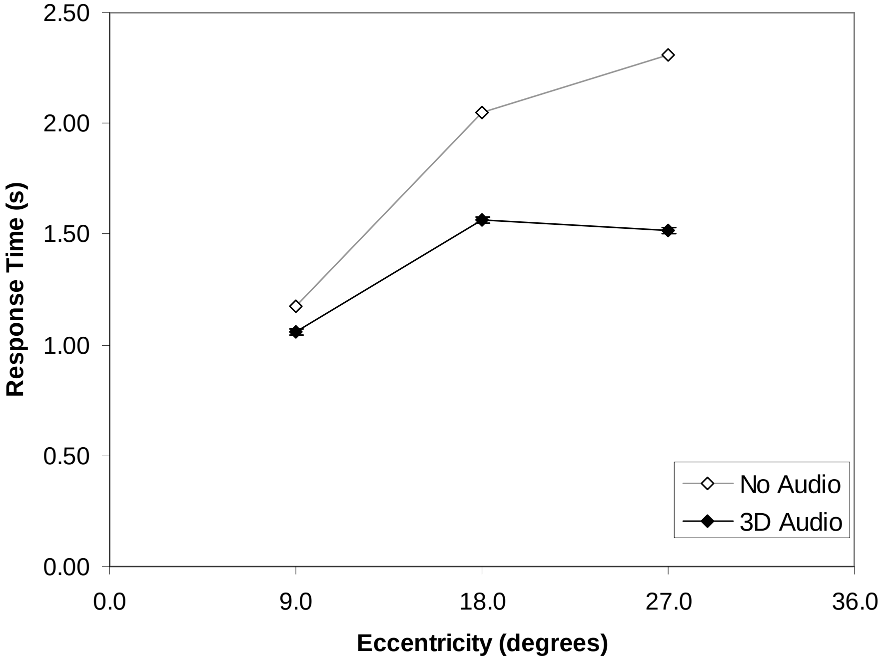


Figure 16. The effects of eccentricity and auditory cues on mean response times. The error bars represent ±1 standard error of the mean and are smaller than the symbols. In the 3D audio condition, response times at 18 and 27 degrees were not significantly different from each other.

The difference between no audio and 3D audio at 9 degrees of eccentricity was evidenced by a post-hoc *t*-test (one-tailed) assuming unequal variances, $t(7915) = 3.359$, $p < 0.001$, a result which corroborates the work of Perrott et al. (1990), who found a beneficial effect of 3D audio (a response time reduction of 175 ms) within 10 degrees of the fixation point. An even larger benefit of 3D audio (480 ms) was found at 18 degrees (a reduction of 23%), and the largest benefit (790 ms) was found at 27 degrees (an impressive reduction of 34%).

In the no audio condition, post-hoc analysis using the Games-Howell test found significant pairwise differences between all three levels of eccentricity (see Appendix B), demonstrating the eccentricity effect: as the eccentricity increased, response times tended to increase. In the 3D audio condition, the post-hoc analysis did not reveal a significant difference between 18 and 27 degrees of eccentricity in the 3D audio condition, but the remaining pairs (9, 18) and (9, 27) were found to be significantly different (see Appendix A). Essentially, targets at 18 degrees of eccentricity were found as fast as targets at 27 degrees when 3D auditory cues were provided. This result is compatible with the idea that 3D audio was able to eliminate the effect of eccentricity between 18 and 27 degrees, a possibility suggested by previous research (e.g., Perrott et al., 1990).

Session. The significant main effect of session, $F(3,21) = 31.534$, $p < 0.001$, indicates training (or practice) effects. As can be seen in Figure 17, observers generally became better at the task as they gained experience, improving by an average of 200 ms from the first to last session (see Figure 17). A post-hoc analysis conducted on the session levels revealed that only sessions 3 and 4 were not significantly different from one another (complete post-hoc results for session are shown in Appendix C); thus, overall performance did not appear to improve past the third session.

Session did *not* interact with any other variable in the overall analysis, which is important to note in the case of auditory cues. Observers appear to have been using the 3D auditory cues as effectively in the first session as in the later sessions. In fact, the average decrease in response times provided by 3D audio (relative to the no audio condition) was 450 ms in the first session and 410 ms in the final session. Thus, 3D audio was able to provide an almost immediate benefit following the single training session

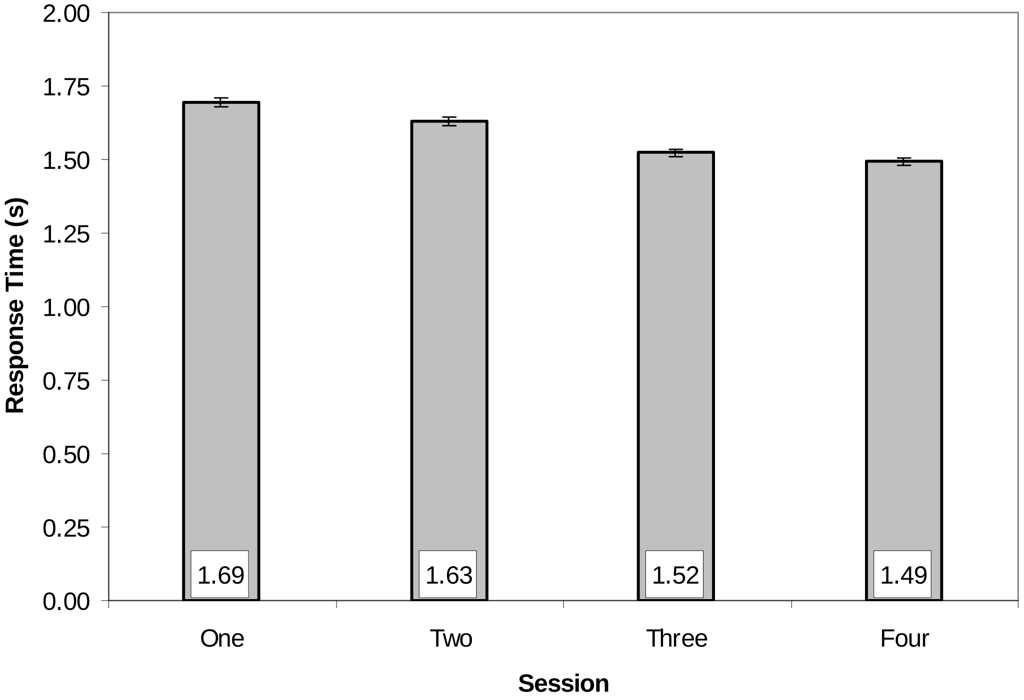


Figure 17. The effect of session on mean response times. The column labels include mean response times, and the error bars represent ±1 standard error of the mean. Sessions Three and Four were not significantly different from each other.

with 300 audio trials and the 50 warm-up trials that preceded each experimental condition, and the benefit was present for each session thereafter. Virtual 3D auditory cues were apparently intuitive, easy to use, and rapidly learned.

Individual Observer Analyses

The results obtained in the overall analysis were very consistent across observers, as shown in Table 1. All main effects of environment, auditory cue, eccentricity, and session were significant at the alpha = 0.05 level *for every observer*, as were the two-way interaction effects of environment by eccentricity and audio by eccentricity. A few other higher-order interactions were significant for some observers, but these were not consistent across observers. In the overall analysis, the type of environment did not interact with the presence of the auditory cue. However, the two-way interaction effect of environment by audio *was* significant for four of the eight observers (see row *Env x Aud* in Table 1).

Table 1

Significant Effects by Observer

				Observer				
Source of Variation	1	2	3	4	5	6	7	8
Main Effects								
Environment (Env)	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
Audio Cue (Aud)	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
Eccentricity (Ecc)	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
Session (Ses)	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
Interaction Effects								
Env * Aud	**xx**	**xx**	**x**			**xx**		
Env * Ecc	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**x**
Aud * Ecc	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**	**xx**
Env * Aud * Ecc								**x**
Env * Ses					**xx**			
Aud * Ses			**xx**					
Env * Aud * Ses			**x**					**x**
Ecc * Ses								
Env * Ecc * Ses			**xx**					
Aud * Ecc * Ses		**x**						
Env * Aud * Ecc * Ses								

Note. The XX's denote p-values of less than 0.01; the X's denote p-values between 0.01 and 0.05.

Subsequent analysis of the four observers who showed a significant environment by audio interaction revealed that 3D audio was *more beneficial* in dynamic environments than in static environments (see Figure 18). For these observers, the difference between the no audio and 3D audio response times was much larger in the dynamic environments, but a beneficial effect of 3D audio was still present in the static environments.

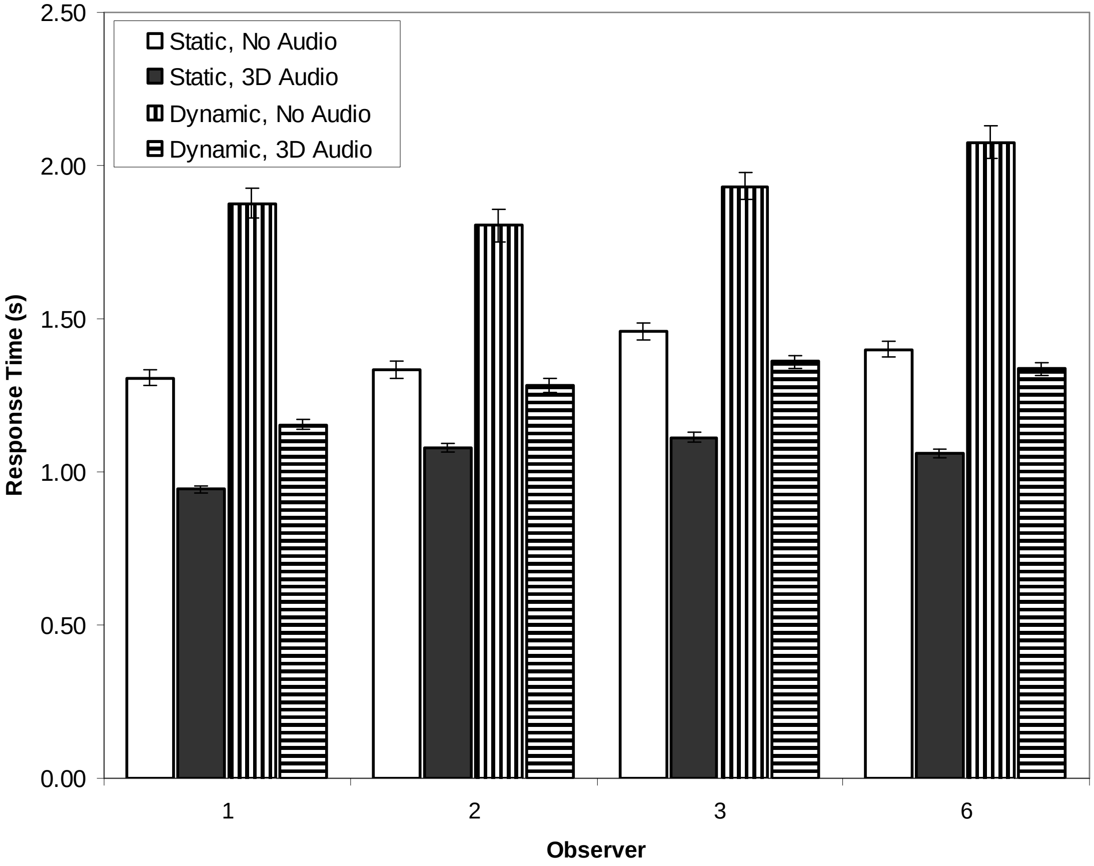


Figure 18. Mean response times by observer, environment, and auditory cue for the four observers who showed *a significant interaction* between environment and auditory cues. The error bars represent ±1 standard error of the mean.

For the four observers who showed no environment by audio interaction, 3D audio reduced response times by similar amounts in both environments (see Figure 19).

Thus, for these observers, 3D audio provided as much help in dynamic environments as in static environments.

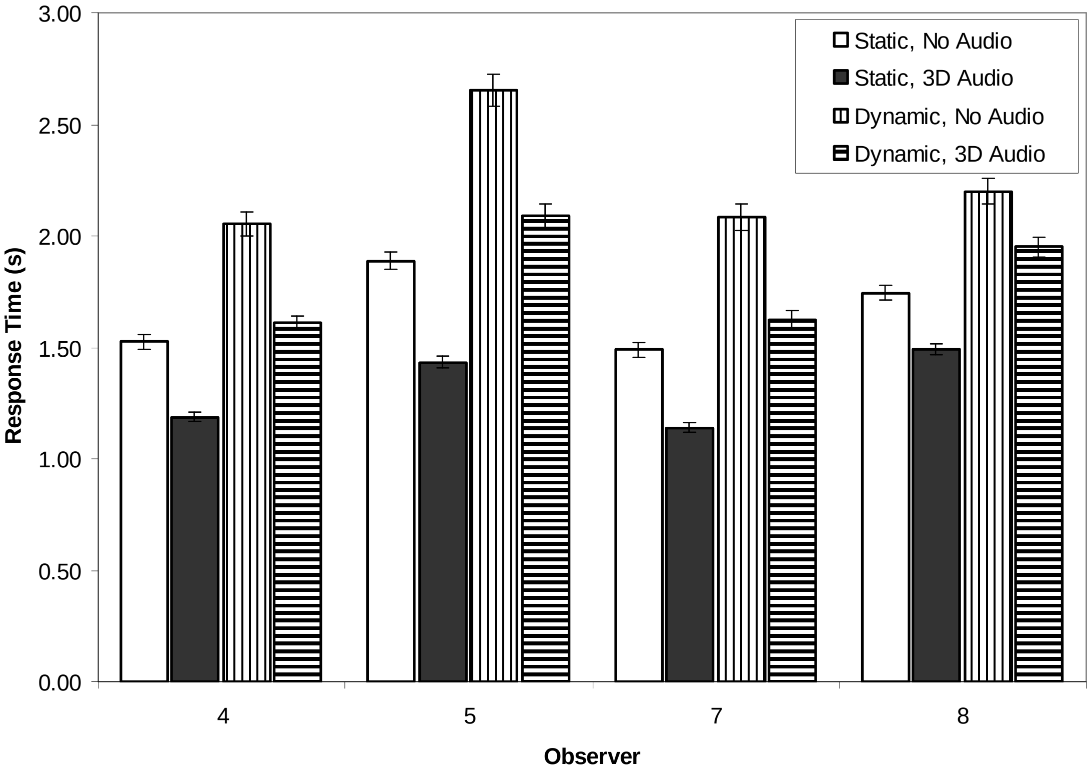


Figure 19. Mean response times by observer, environment, and auditory cue for the four observers who showed *no interaction* between environment and auditory cues. The error bars represent ±1 standard error of the mean.

Analysis of Direction of Target Motion

A separate analysis was performed using only trials in the dynamic environments. This exclusion of static trials was necessary to examine what effect (if any) the direction of target motion had on response times. Again, the target starting location was excluded to avoid confounding eccentricity with location. In this analysis, the independent variables under investigation were auditory cue, eccentricity, session, and direction of target motion. Although there were eight possible directions of movement in the experiment (up, down, left, right, and the four obliques between them), each direction was grouped into one of three levels: horizontal, vertical, or oblique motion. Grouping in this manner avoided problematic instances where a target started moving in one direction, then “bounced-off” the edge of the image using realistic physics to stay within the display area before being detected. In other words, by using this grouping, horizontal motion was always horizontal motion, vertical was always vertical, and oblique was always oblique.

Consistent with the overall analysis, there were significant main effects of auditory cue, eccentricity, and session, and a significant interaction effect of auditory cue and eccentricity. There were three significant effects involving the direction of target motion: the main effect of direction of motion; the interaction of motion and auditory cues; and the interaction of motion and eccentricity. Only the main effect of direction and its interaction with auditory cues will be discussed further, although the complete ANOVA tables are presented in Appendix D.

The main effect of direction of target motion was significant, F(2,14) = 293.915, $p < 0.001$ (shown in Figure 20). In general, response times for the horizontally-moving targets were fastest, response times for vertically-moving targets were slowest, and response times for obliquely-moving targets fell between the two. Post-hoc analysis revealed significant pairwise differences between horizontal, vertical, and oblique directions of motion (see Appendix E).

The significant interaction effect of direction of target motion by auditory cues revealed a similar pattern to the main effect, F(2,14) = 42.060, $p < 0.001$. As shown in Figure 21, response times in both auditory conditions were fastest for horizontally-

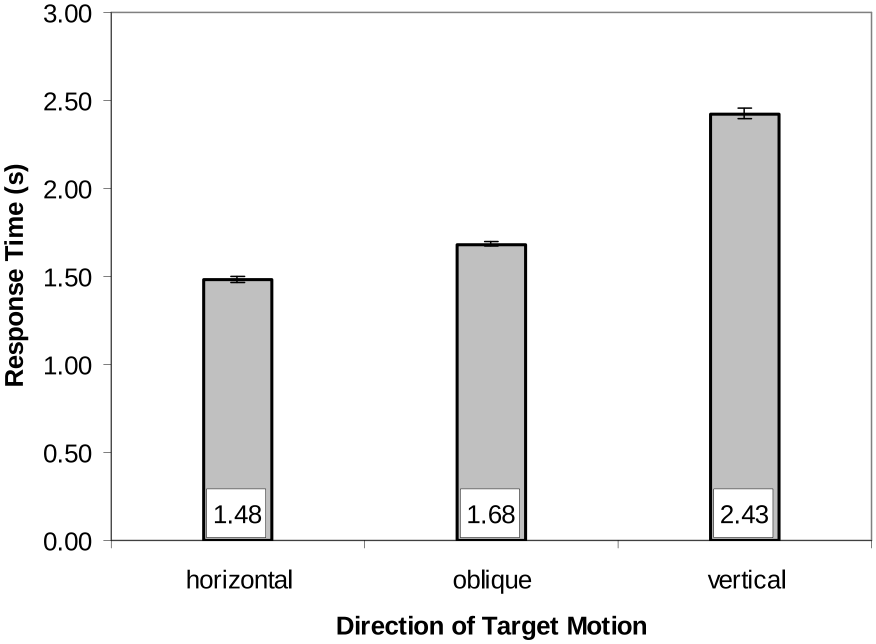


Figure 20. The effect of direction of target motion on mean response times. The column labels include mean response times, and the error bars represent ±1 standard error of the mean.

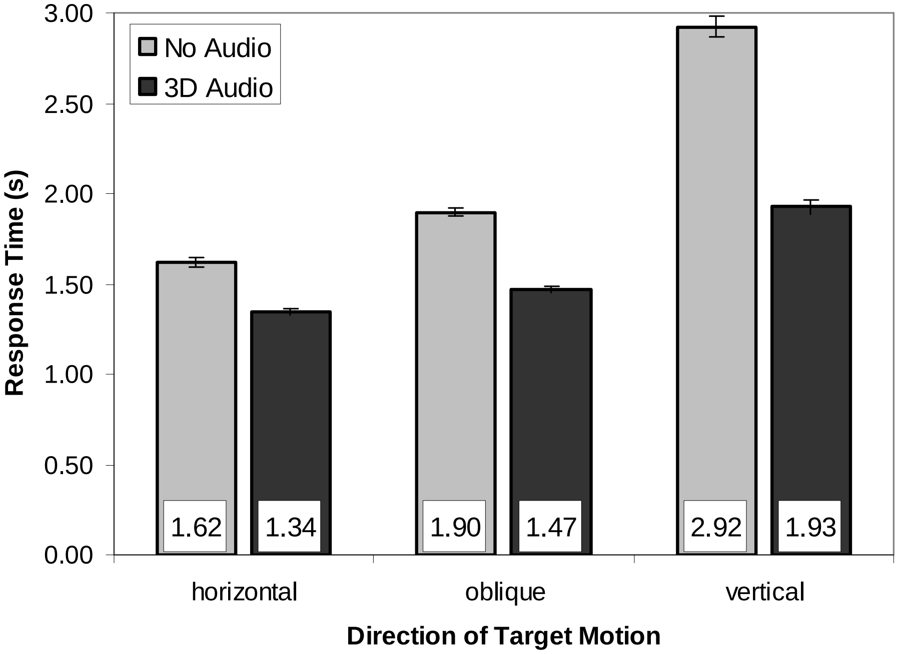


Figure 21. The effects of direction of target motion and auditory cues on mean response times. The column labels include mean response times, and the error bars represent ±1 standard error of the mean.

moving targets and slowest for vertically-moving targets, with obliquely-moving targets falling between the two.

Note that in the no auditory conditions, the direction of motion greatly influenced response times, which was unexpected. It would be a very interesting and important result to find that the direction of the moving target truly had such an effect on unaided search times. However, the effect that we found was probably due to an unintended artifact on the visual display. For the moving targets, there was a “blurring” of the gap, which was always present for vertically moving targets and partially present for obliquely moving targets, but not present at all for horizontally moving targets. This confounding factor could easily explain why the direction of the target motion effected response times in the no audio conditions. So instead of varying only the direction of target motion, we also inadvertently manipulated the visibility of the target.

Despite this confounding factor, it seems apparent from our results shown in Figure 21 that, in the no audio conditions, targets moving vertically were more difficult to find than obliquely moving targets, which were more difficult to find than horizontally moving targets. Thus, in this analysis, the direction of target motion could be considered as an “index of difficulty.” Keeping this in mind, the results show that 3D audio was able to temper the added difficulty of finding targets moving in particular directions. Under the easiest dynamic condition (targets moving horizontally), 3D audio reduced search times by 280 ms (17%). Under moderate difficulty (targets moving obliquely), 3D audio reduced search times by 430 ms (23%). Under the most difficult dynamic condition (targets moving vertically), 3D audio reduced search times by approximately one second

(34%). These results, in concurrence with previous research (e.g., Bolia et al., 1999), suggest that the benefit of 3D audio grows with the difficulty or complexity of the search.

Analysis of Target Starting Location

To investigate the target's starting location (or angle) relative to the fixation cross, equal numbers of eccentricities were needed at each angle to avoid confounding eccentricity with angle. Therefore, this analysis excluded trials with starting points at 27 degrees of eccentricity so that the same number of eccentricities were present for each level of the starting location angles. There were eight possible angles for target starting locations (relative to the fixation cross): 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. These eight angles were grouped into three levels: horizontal (0° and 180°), oblique (45°, 135°, 225°, and 315°), and vertical (90° and 270°) as shown in Figure 22. The independent variables were environment, auditory cue, eccentricity, and angle of the target starting location; the session variable was excluded from this analysis.

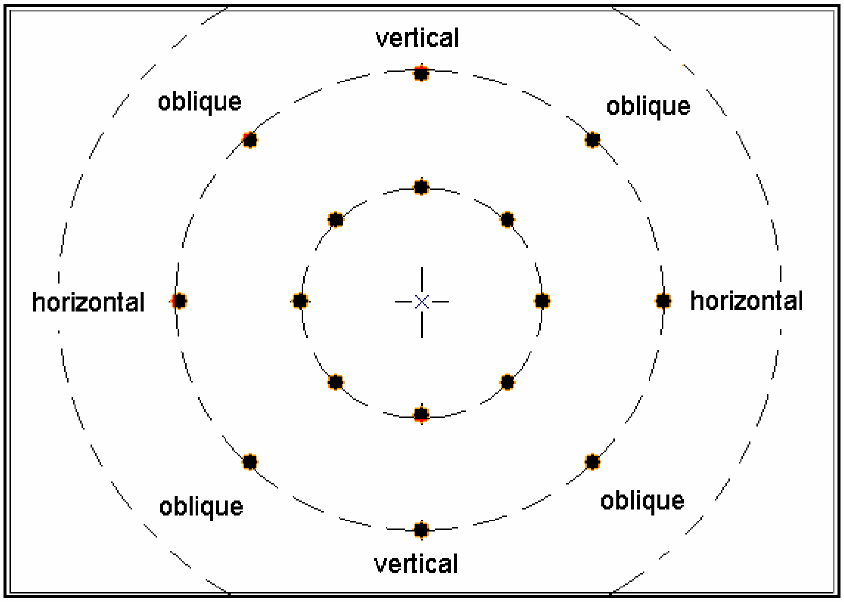


Figure 22. In the analysis of angle of target starting location, only trials with target starting positions at 9 or 18 degrees of eccentricity were included (positions at 27 degrees of eccentricity were excluded). The eight angles were grouped into three levels: horizontal, vertical, and oblique.

Results in this amended analysis were similar to the overall analysis: there were significant main effects of environment, auditory cue, and eccentricity, and interaction effects of environment by eccentricity and audio by eccentricity (see Appendix F for a complete ANOVA table). There were several significant effects involving the angle of the target's starting location. The main effect of angle of target starting location was significant, F(2,14) = 30.791, $p < 0.001$ (shown in Figure 23). This result reveals that

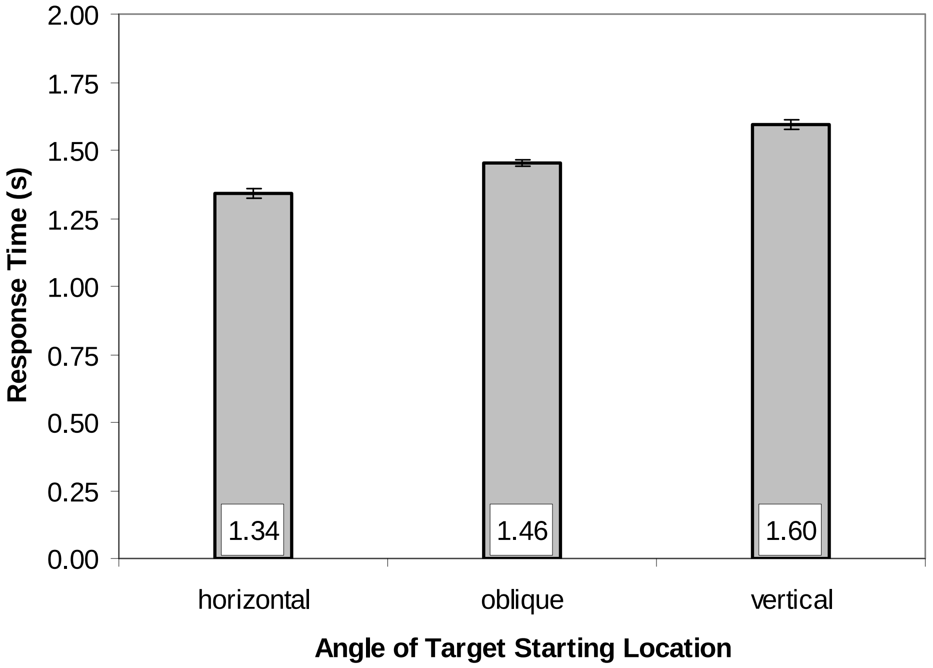


Figure 23. The effect of the angle of target starting location on mean response times. The column labels include mean response times, and the error bars represent ±1 standard error of the mean.

response times were fastest for targets appearing at a horizontal angle (1.34 s) and slowest for targets starting at a vertical angle (1.60 s). Response times for targets appearing at an oblique angle fell between horizontal and vertical angles (1.46 s). Post-hoc analysis of the main effect of starting location revealed significant pairwise differences between horizontal, oblique, and vertical angles of target starting location (see Appendix G).

In addition, there were significant interaction effects of environment by target angle, F(2,14) = 4.094, $p = 0.040$, audio cue by target angle, F(2,14) = 22.067, $p < 0.001$ (shown in Figure 24), and audio cue by eccentricity by target angle, F(2,14) = 11.939, $p = 0.001$. The benefit provided by 3D audio (i.e., the difference between the no audio and 3D audio conditions) is largest for targets appearing at a horizontal angle (400 ms or 26%) and smallest for targets appearing at a vertical angle (250 ms or 15%). The benefit provided by 3D audio for targets appearing at an oblique angle again fell between these two results (270 ms or 17%). Post hoc analysis revealed significant pairwise differences between horizontal, oblique, and vertical angles of target starting location for both audio conditions.

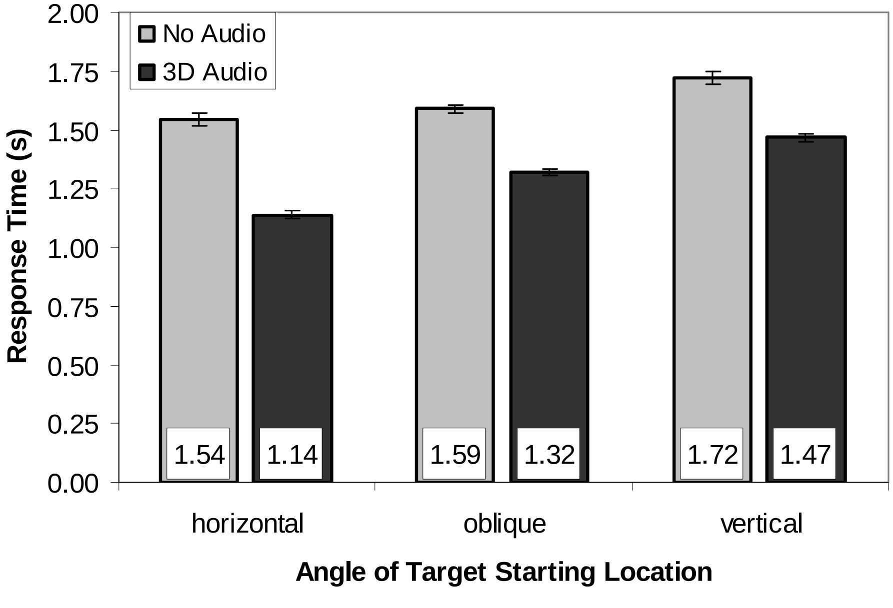


Figure 24. The effects of the angle of target starting location and auditory cues on mean response times. The column labels include mean response times, and the error bars represent ±1 standard error of the mean.

It is not immediately clear why the angle of the target's starting location affected response times in the no audio conditions. We believed that when no auditory cues were given, search times should have been unaffected by the angle of the target's starting location. We speculate that this finding reflects a tendency for observers to start their search with eye movements to the left or right (as opposed to up or down). This tendency could reflect a general bias in human search behavior (Megaw & Richardson, 1979), but more likely it is due to the fact that the display used in this experiment was wider horizontally than vertically, creating more target starting positions left/right than up/down (see Figure 5). Thus, observers had a higher chance of spotting the target with immediate left/right eye movements, and they may have adapted their search strategy accordingly.

It seems clear, however, why the benefit provided by 3D audio depended upon the location of the target. Previous research has repeatedly suggested that the localization of a sound on the horizontal axis is relatively precise because the interaural time and intensity level differences (ITD and ILD) are especially robust cues for localization (Wightman & Kistler, 1993). In contrast, localization of sounds in the vertical dimension is less precise because the only available cues to elevation are spectral changes caused by reflections of a sound off of the head, neck, shoulders, torso, and outer ear (pinnae). In fact, Grantham (1986) measured the minimum audible angle (MAA) in the horizontal dimension at about 1 degree, while Perrott and Saberi (1990) measured the MAA in the vertical dimension at about 4 degrees.

Thus, both theory and experimental results suggest that the information about the elevation of a sound is generally more ambiguous than the information about the azimuth. In the present study, the use of HRTFs that were not specific to each observer could also have exacerbated the difficulty of finding vertical targets using virtual sound cues. Indeed, Wenzel, Arruda, Kistler, and Wightman (1993) found that using non-individualized HRTFs resulted in distorted perceptions of elevation. These considerations imply that 3D auditory cues should be most effective for targets located at a horizontal angle, less effective for targets at oblique angles (which contain a mixture of both horizontal and vertical location information), and least effective for targets located at a vertical angle (which contain only vertical information). Indeed, the results showed precisely this effect.

IV. CONCLUSIONS AND FUTURE RESEARCH

Before conducting this research, we were unsure what effect 3D audio would have upon visual search performance in a dynamic environment when compared to a static environment. Previous research and theory suggested at least two possibilities. One possibility was that 3D audio would be even more beneficial in dynamic environments than in static environments, due to the added difficulty of searching for a moving target hidden among moving distractors; the research of Bolia et al. (1999) showed that 3D audio tended to provide a larger benefit as the search difficulty was increased. An alternative possibility was that the poorer localization accuracy for moving auditory cues (Grantham, 1994) would translate into a reduced benefit of 3D audio in dynamic environments. In either case, we suspected that 3D audio would at least provide some benefit in dynamic environments.

The results of this experiment clearly show that 3D audio cues can be just as effective (if not more so) in dynamic environments as in static environments. In fact, a beneficial effect of 3D audio was found for *all participants*, in both static and dynamic environments. These results allow designers and researchers to more confidently assume that the conclusions drawn from research in static environments will indeed transfer to environments with moving stimuli.

The results also show that 3D audio can be effective for visual cuing even in relatively small search areas (in this study, the search area was 60 degrees horizontal by

47 degrees vertical). In addition, 3D audio was even effective at reducing search times within 9 degrees of the fixation point. These results, and the results of previous researchers (e.g., Perrott et al., 1990), make 3D audio an attractive option for cuing on personal computer displays, control panels, work stations, and in other unique operating systems.

The ability of 3D auditory cues to provide even greater benefits as the search difficulty increases (i.e., with larger effective search areas or with moving targets and distractors) suggests that auditory cuing could prove especially useful in complex operating environments. Under the most difficult conditions (i.e., searches for vertically moving targets), 3D audio was able to reduce response times by about one second. In time-critical operating environments, such as cockpits, ground-vehicle crew stations, command and control workstations, and other military environments, a single second can mean the difference between life and death.

In this experiment, the 3D auditory cues were displayed to observers with a single set of HRTFs that were not their own. Yet, every observer was able to readily use the 3D auditory cues as an effective search aid. This finding implies that investigators and designers hoping to use virtual audio may not need to obtain individualized HRTFs for each operator, which may be technically or economically infeasible. The observers seemed to perform very well using non-individualized HRTFs, but further research is necessary to clarify this issue.

The lack of an interaction effect between the auditory cue and session variables shows that observers were able to effectively use the auditory cues almost immediately. Indeed, 3D audio was just as effective in the first session as the last. The relatively short training sessions (300 practice trials with auditory cues plus 50 trial warm-ups before each experimental condition) were apparently enough to allow efficient use of 3D audio. This finding is important for designers and researchers who might worry about how much training with 3D audio is appropriate. However, it remains unclear exactly how much training is necessary or optimal; again, further research is needed to clarify this issue.

Although the overall results of this experiment are suggestive in terms of the usability of 3D audio, the lack of research in this area concerning dynamic search environments makes it difficult to predict how other manipulations might affect performance. These manipulations could include varying the speed of the target, the number of distractors, the size or complexity of the visual target, the number of targets, the types of motion, types and characteristics of auditory cues, or the size of the search area. Since 3D audio could prove especially useful in military environments, further research could also examine the effects of 3D audio on dynamic visual search while wearing ear protection, helmets, head-mounted displays (HMDs), or night-vision goggles (NVGs). The effect of auditory noise (which is present in practically every real-world environment) on aurally-aided dynamic visual search might also prove to be a fruitful research area. In addition, consider that in most operating environments the auditory channel may already be in use by voice communications or other auditory displays, so knowing how these interact with spatial auditory displays may be critical.

Current applications of 3D audio technologies are implicitly based on the assumption that the previous results shown in the literature will remain valid in more complex operating environments, despite the transference of the technology from static to dynamic environments. Although many future research questions remain, the present research suggests that this assumption of transference is warranted, and that 3D auditory technology will likely prove extremely beneficial to operators in dynamic environments.

APPENDIX A
Overall Analysis: ANOVA Results

Table A1

Overall Analysis: ANOVA Results

Source	Sum of Squares	df	Mean Square	F	Sig
Environment (Env)	57.288	1	57.288	330.654	.000
error	1.213	7	.173		
Audio Cue (Aud)	51.307	1	51.307	97.595	.000
error	3.680	7	.526		
Eccentricity (Ecc)	311.585	2	155.793	153.823	.000
error	14.179	14	1.013		
Session (Ses)	8.860	3	2.953	31.534	.000
error	1.967	21	.094		
Env * Aud	.254	1	.254	1.801	.221
error	.986	7	.141		
Env * Ecc	5.112	2	2.556	42.143	.000
error	.849	14	.061		
Env * Ses	.024	3	.008	.148	.930
error	1.135	21	.054		
Aud * Ecc	21.025	2	10.512	96.822	.000
error	1.520	14	.109		
Aud * Ses	.066	3	.022	.567	.643
error	.819	21	.039		
Ecc * Ses	.453	6	.076	2.141	.069
error	1.482	42	.035		
Env * Aud * Ecc	.114	2	.057	1.889	.188
error	.421	14	.030		
Env * Aud * Ses	.003	3	.001	.023	.995
error	.823	21	.039		
Aud * Ecc * Ses	.187	6	.031	.916	.493
error	1.429	42	.034		
Env * Aud * Ecc * Ses	1.168	6	.011	.385	.885
error	1.213	42	.028		

Note: Error terms were calculated using the variable x participant interactions.

APPENDIX B
Post-hoc tests on eccentricity using the Games-Howell test

Table A2

Levels of the Main Effect of Eccentricity

Eccentricity I	Eccentricity J	Mean Difference (I – J)	Std. Error	Sig
9	18	-.2288	.00330	< .001
9	27	-.2655	.00335	< .001
18	9	.2288	.00330	< .001
18	27	-.0367	.00322	< .001
27	9	.2655	.00335	< .001
27	18	.0367	.00322	< .001

Table A3

Levels of Eccentricity in the Static Condition

Eccentricity I	Eccentricity J	Mean Difference (I – J)	Std. Error	Sig
9	18	-.2481	.00361	< .001
9	27	-.3035	.00384	< .001
18	9	.2481	.00361	< .001
18	27	-.0554	.00399	< .001
27	9	.3035	.00384	< .001
27	18	.0554	.00399	< .001

Table A4

Levels of Eccentricity in the Dynamic Condition

Eccentricity I	Eccentricity J	Mean Difference (I – J)	Std. Error	Sig
9	18	-.2090	.00518	< .001
9	27	-.2269	.00519	< .001
18	9	.2090	.00518	< .001
18	27	-.0179	.00485	.001
27	9	.2269	.00519	< .001
27	18	.0179	.00485	.001

Table A5

Levels of Eccentricity in the No Audio Condition

Eccentricity I	Eccentricity J	Mean Difference (I – J)	Std. Error	Sig
9	18	-.2719	.00497	< .001
9	27	-.3420	.00488	< .001
18	9	.2719	.00497	< .001
18	27	-.0700	.00457	< .001
27	9	.3420	.00488	< .001
27	18	.0700	.00457	< .001

Table A6

Levels of Eccentricity in the 3D Audio Condition

Eccentricity I	Eccentricity J	Mean Difference (I – J)	Std. Error	Sig
9	18	-.1854	.00417	< .001
9	27	-.1881	.00402	< .001
18	9	.1854	.00417	< .001
18	27	-.0027	.00380	.759
27	9	.1881	.00402	< .001
27	18	.0027	.00380	.759

APPENDIX C
Post-hoc tests on session using the Games-Howell test

Table A7

Levels of the Main Effect of Session

Session I	Session J	Mean Difference (I – J)	Std. Error	Sig
1	2	.0170	.00446	.001
1	3	.0430	.00444	< .001
1	4	.0510	.00441	< .001
2	1	-.0170	.00446	.001
2	3	.0260	.00444	< .001
2	4	.0340	.00441	< .001
3	1	-.0430	.00444	< .001
3	2	-.0260	.00444	< .001
3	4	.0080	.00439	.262
4	1	-.0510	.00441	< .001
4	2	-.0340	.00441	< .001
4	3	-.0080	.00439	.262

APPENDIX D
Analysis of Direction of Target Motion: ANOVA Results

Table A8

Analysis of Direction of Target Motion: ANOVA Results

Source	Sum of Squares	df	Mean Square	F	Sig
Audio Cue (Aud)	28.425	1	28.425	56.973	.000
error	3.493	7	.499		
Eccentricity (Ecc)	103.294	2	51.647	124.823	.000
error	5.793	14	.414		
Direction (Dir)	47.257	2	23.629	293.915	.000
error	1.126	14	.080		
Session (Ses)	4.553	3	1.518	14.702	.000
error	2.168	21	.103		
Aud * Ecc	7.728	2	3.864	45.468	.000
error	1.190	14	.085		
Aud * Dir	3.846	2	1.923	42.060	.000
error	.640	14	.046		
Aud * Ses	.053	3	.018	.389	.762
error	.959	21	.046		
Ecc * Dir	14.286	4	3.571	58.464	.000
error	1.711	28	.061		
Ecc * Ses	.428	6	.071	1.971	.092
error	1.520	42	.036		
Dir * Ses	.154	6	.026	.812	.566
error	1.323	42	.031		
Aud * Ecc * Dir	.261	4	.065	2.320	.082
error	.787	28	.028		
Aud * Ecc * Ses	.052	6	.009	.228	.965
error	1.614	42	.038		
Ecc * Dir * Ses	.250	12	.021	.715	.732
error	2.450	84	.029		
Aud * Ecc * Dir * Ses	.240	12	.020	.584	.849
error	2.880	84	.034		

Note: Error terms were calculated using the variable x participant interactions.

APPENDIX E

Post-hoc tests on direction of target motion using the Games-Howell test

Table A9

Levels of the Main Effect of Direction

Direction I	Direction J	Mean Difference (I – J)	Std. Error	Sig
horizontal	oblique	-.0512	.00521	< .001
horizontal	vertical	-.1866	.00653	< .001
oblique	horizontal	.0512	.00521	< .001
oblique	vertical	-.1354	.00582	< .001
vertical	horizontal	.1866	.00653	< .001
vertical	oblique	.1354	.00582	< .001

APPENDIX F
Analysis of Target Starting Location: ANOVA Results

Table A10

Analysis of Target Starting Location: ANOVA Results

Source	Sum of Squares	df	Mean Square	F	Sig
Environment (Env)	52.456	1	52.456	439.311	.000
error	.836	7	.119		
Audio Cue (Aud)	14.088	1	14.088	39.547	.000
error	2.494	7	.356		
Eccentricity (Ecc)	187.535	1	187.535	150.770	.000
error	8.707	7	1.244		
Angle (Ang)	14.073	2	7.036	30.791	.000
error	3.199	14	.229		
Env * Aud	.448	1	.448	4.306	.077
error	.728	7	.104		
Env * Ecc	1.452	1	1.452	17.478	.004
error	.582	7	.083		
Env * Ang	.549	2	.275	4.094	.040
error	.939	14	.067		
Aud * Ecc	7.254	1	7.254	35.738	.001
error	1.421	7	.203		
Aud * Ang	1.371	2	.685	22.067	.000
error	.435	14	.031		
Ecc * Ang	.351	2	.176	2.571	.112
error	.957	14	.068		
Env * Aud * Ecc	.000	2	.000	.004	.954
error	.158	14	.023		
Env * Aud * Ang	.241	2	.121	1.971	.176
error	.856	14	.061		
Aud * Ecc * Ang	.645	2	.322	11.939	.001
error	.378	14	.027		
Env * Aud * Ecc * Ang	.147	2	.073	2.174	.151
error	.473	14	.034		

Note: Error terms were calculated using the variable x participant interactions.

APPENDIX G

Post-hoc tests on angle of target starting location using the Games-Howell test

Table A11

Levels of the Main Effect of Angle

Angle I	Angle J	Mean Difference (I – J)	Std. Error	Sig
horizontal	oblique	-.0411	.00459	< .001
horizontal	vertical	-.0838	.00531	< .001
oblique	horizontal	.0411	.00459	< .001
oblique	vertical	-.0427	.00457	< .001
vertical	horizontal	.0838	.00531	< .001
vertical	oblique	.0427	.00457	< .001

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