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What is This?

# Auditory Spatial Facilitation of Visual Search Performance: Effect of Cue Precision and Distractor Density

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Two experiments examined auditory spatial facilitation of visual search performance under conditions varying in auditory cue precision and visual distractor density. The auditory cue was spatially coincided with the target, was displaced from the target by 6°, or was uninformative. Distractors were manipulated globally (throughout the field) and locally (within 6.5° of the target) separately at densities of 0%, 20%, and 80%. In Experiment 1, auditory cue precision was constant and distractor densities varied within a trial block; in Experiment 2, auditory precision varied and distractor densities were constant within a trial block. Coincident auditory cues minimized local and global distractor effects in both experiments, suggesting that auditory spatial cues facilitate both target localization and identification. The effectiveness of displaced auditory cues depended on cue reliability: In some conditions, displaced cues caused higher mean search latencies than did centered cues, indicating that participants were unable to ignore inaccurate auditory stimuli. Actual or potential applications of this research include virtual audio environments and auditory displays in cockpits.

## INTRODUCTION

Virtual environments often contain simulations of auditory reality in addition to visual reality. Auditory virtual environments are produced by replicating two cues known to be important for sound-source localization: interaural difference cues and cues related to the action of the pinna on incoming sources (e.g. Wenzel, Wightman, & Foster, 1988; Wightman & Kistler, 1989). The pinna cues are replications of the magnitude and phase characteristics of the head-related transfer function (HRTF) and produce the perception of externalized sound images at a particular elevation and azimuth when presented via earphones. These three-dimensional (3D) audio cues have been credited with performance improvements in many settings for both auditory and visual tasks in real- and virtual-displays. Benefits to auditory tasks include improved speech intelligibility, audio feedback and alerts in the cockpit, and improved acoustic-signal recognition in sonar systems (Begault, 1995; Doll & Hanna, 1997; McKinley & Ericson, 1997). In visual tasks, auditory 3D cues can improve traffic detection and avoidance, target acquisition, and visual workload in the cockpit (Begault, 1993; McKinley et al., 1995; McKinley & Ericson, 1997).

Auditory 3D cuing benefits visual search performance because auditory 3D displays take advantage of the strengths of the auditory system relative to vision. Although the visual system is vastly superior to the auditory system on spatial acuity tasks, the human auditory system can detect and localize sounds from any direction around the listener without any movement of the sensory apparatus (e.g., Middlebrooks & Green, 1991). Furthermore, auditory events are localized in reference to the position of the listener (e.g., Fisher &

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Freedman, 1968; Perrott, Saberi, Brown, & Strybel, 1990). Using auditory spatial cues to indicate the location of a visual target exploits the omnidirectional attribute of the human auditory system and provides a natural means of cuing an observer, such as a pilot, as to visual events in the environment.

In the laboratory, auditory spatial cues significantly reduce the time to find visual targets. Perrott et al. (1990) demonstrated that the time to locate and identify a single visual target in a 260° horizontal search field was reduced by 150 to 800 ms when an auditory stimulus, located at the target, was presented simultaneously with the target. When vertical uncertainty was added to the task, the facilitation increased to approximately 1000 ms. Perrott, Cisneros, McKinley, and D'Angelo (1995, 1996) measured the effect of auditory spatial cues in a visual search task with a 360° horizontal by 160° vertical search field. In the absence of auditory spatial information, search times were lowest (<1250 ms) for targets within 50° horizontally and 40° vertically. When auditory cues were spatially coincident with the visual target, search times were less than 1250 ms for nearly the entire search field.

Although the greatest benefits of auditory spatial cuing are accrued for peripheral targets, search performance also improves when the targets are located in the central visual field. Perrott et al. (1990) obtained reductions of 150 to 200 ms for visual targets within 10° of fixation. Perrott, Sadralodabai, Saberi, and Strybel (1991) found the benefits of auditory spatial cues in the central visual field to depend on target distance and the number of visual distractors present. For targets located within 2.4° of fixation, search times fell by 30 ms when auditory spatial cues were present. When the targets were located 15° from fixation, the auditory spatial cue lowered search times by 100 ms and minimized the effects of number of distractors. The slope of search time as a function of number of distractors in the auditory spatial cue condition was nearly half that of the no-cue condition (4.8 vs. 9.4 ms/distractor). Strybel, Boucher, Fujawa, and Volp (1995) found that improvements in search performance produced by auditory spatial cues rely on target distance and contrast: When auditory spatial cues were present, the detrimental effects of both distance and contrast on visual search times were minimized.

In summary, laboratory research has shown that auditory spatial cues significantly reduce the time to locate and identify a visual target, with the amount of benefit depending on variables such as search field size, number of distractors, target distance, and target contrast. Perrott et al. (1996) found that visual search times with simulated 3D cues were no more than 200 ms higher than with actual audio spatial cues. Thus both real and simulated auditory spatial cuing can potentially produce dramatic improvements in visual search performance for both real and virtual environments.

Before simulated 3D cues can be successfully implemented in the workplace, however, questions about the optimal design of the audio display and the mechanism of the auditory spatial facilitation effect need to be addressed. One important design issue is the required precision of the display. Most 3D audio technologies store HRTFs for only a finite set of locations and interpolate the HRTF for intermediate locations. Although it reduces the cost and storage requirements for the display, this strategy can degrade the precision of the auditory 3D cue in specifying the location of the target. Currently there is little knowledge on the effect of degraded auditory cues on visual search. It is likely that the precision requirements will depend on the visual environments and task characteristics. For example, auditory cuing in an environment that provides a high amount of visual information to a target's location may not need to be as precise as when little or no visual target information is present.

Not only may auditory cue precision requirements be affected by the amount of visual information, but auditory precision may depend on the mechanisms or processes involved in auditory spatial facilitation. Williams (1973) partitioned visual search into two general stages: *localization,* accomplished by moving the eyes to a region of potential targets, and *identification,* accomplished by fixating on each potential target and deciding whether it is the target. Drury and Clement (1978) estimated the size of the area fixated

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upon in the identification stage, or local target area, to be 7.5° for a distractor density of 16% and 5.5° for a distractor density of 100% by estimating the number of potential targets, or distractors, perceived in a single fixation. If auditory spatial cues affect only the localization stage, precision will be less important because the cue would specify only a general location. If the identification stage were affected, cue precision would be critical – auditory events would have to appear spatially equated with visual target locations for the maximum benefits of auditory spatial facilitation to occur.

Only one experiment has reported on the effects of degrading the accuracy of the auditory spatial cue in a visual search task. Perrott et al. (1996) compared simulated two-dimensional (2D) auditory cues, simulated 3D cues, and actual sound sources that were spatially coincident with the visual target. As previously noted, small performance decrements were obtained when simulated 3D sound cues were compared with actual sources; however, performance with the simulated 2D cue was not different from performance with the simulated 3D cue over most of the search field. This suggests that observers used the auditory spatial cue to signal only the general location of the target and used visual information to search within the local target area. Perrott et al. did not present distractors with the target, however, so it is impossible to analyze the effect of the cue on each stage of search and under different conditions of visual information.

Another important consideration for the design of auditory 3D displays is the degree to which the cue is under the observer's control. In visual attention literature, a distinction is made between endogenous cues – those used strategically by observers to optimize search performance – and exogenous cues, which pull an observer's attention toward the cue. If auditory 3D cues are exogenous, an observer would be less able to ignore an inaccurate or less-important auditory cue, thus interfering with performance. Recent research has obtained both endogenous and exogenous effects of auditory spatial cuing. For example, Strybel et al. (1995) found that the amplitude of the auditory cues reduced search times only when the cue was coincident with the target, as would be expected with exogenous cuing. However, when visual uncertainty was added to the task, amplitude had no effect; observers used high-amplitude cues (70 dB A-weighted) and low-amplitude cues (40 dB A-weighted) equally well. This suggests an endogenous, strategic shift in the weighting of the information contained in the auditory spatial cue. By manipulating the validity of the auditory spatial cue, whether the cues were spatially positioned to coincide with the target or in the hemisphere opposite that of the target, Fujawa and Strybel (1997) demonstrated that as the percentage of valid cues decreased in a trial block, there was less difference in search times between valid and invalid cues, suggesting endogenous cuing. However, high-amplitude cues significantly improved search performance of valid cues and degraded search performance with invalid cues, as would be expected with exogenous cuing. The minimal amount of evidence on endogenous versus exogenous auditory spatial cuing suggests that both types may be involved.

In summary, although the potential benefits and applications of auditory 3D cues have been well documented, the mechanisms involved have not. The present experiments attempted to resolve these issues by testing whether auditory spatial cuing affects the localization stage of visual search, the identification stage, or both stages by manipulating the density of distractors within the local area around the target and within the entire search field. Additionally, we estimated the effect of degrading the precision of the auditory cue on visual search performance by manipulating whether the auditory spatial cue pointed to the exact location of the target, the local area around the target, or the center of the visual field, which provided no spatial information about the target. Finally, we manipulated the reliability of the cues to determine whether observers could ignore inaccurate auditory spatial cues.

## EXPERIMENT 1: RELIABLE AUDITORY CUES

In the first experiment we manipulated the density of distractors around the target and in

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the overall search field separately in order to determine whether auditory spatial cuing affects target localization or identification. If auditory spatial cues indicate only the local area around the target, then there should be no benefit of the auditory cue when the density of global distractors is low. In contrast, if auditory spatial cues affect target identification, a reduction in search performance would be expected even when distractors are not present in the overall search field. In addition to the manipulation of distractor density, the auditory spatial cue was coincident with the target, displaced from the target, or located at the initial fixation point (providing no target information). Within a trial block, the auditory spatial cue condition was constant, and observers were informed about the target information contained in the auditory stimulus.

## Method

*Participants.* Six students, including the first author, served as observers. All had normal hearing and normal or corrected-to-normal vision. None had previously participated in an auditory spatial cuing experiment.

*Apparatus.* The experiment was conducted in a 3.6 × 4.9 m room with all surfaces covered with Markerfoam 10.16-cm acoustic foam sheets. The reported absorption coefficients for this product exceed .90 for frequencies greater than 250 Hz. Participants sat in the middle of the room facing a large white projection screen 133.35 cm distant. The projection screen, made of polyester, was acoustically but not visually transparent. Mounted behind the screen were 29 Blaupunkt 7.6-cm loudspeakers arranged in two circular rings. Visual stimuli were projected onto the screen with a Sayett Data Show 480 projection panel and overhead projector located in the test chamber above and behind the participant. The effective visual field created by the projection system was 55° horizontally and 42° vertically. The luminance of the screen was 9.01 cd/m$^2$, and the contrast of the stimuli was 75%. The background luminance in the test room was 0.14 cd/m$^2$. The ambient noise level in the test room, created by the projection system, was 41.9 dB, A-weighted with an upper frequency limit of 1000 Hz. The projector noise was low pass of 42 dB A-weighted with an upper frequency cutoff of 1 kHz and 6 dB/octave roll-off.

The projection panel was attached to a computer located in an adjacent room. The computer controlled all aspects of the experiment: order of trials, stimulus presentation, speaker selection, auditory cue activation, response collection, and timing. The auditory cues were presented from one of the speakers by means of Tucker-Davis Technologies audio modules interfaced with the computer. The auditory cues always consisted of bandpass noise (1800–8000 Hz) at 55 dB, A-weighted.

The target stimulus consisted of two equal-length lines of four pixels forming a right angle, covering a visual angle of approximately 1°, and pointing either to the right or the left. The direction of the target (right or left) was random, as was the hemisphere in which the target was presented. Distractor stimuli were identical to the target stimuli but were rotated to point up or down. The target was located at one of two distances from the fixation point: 14.9° or 29.7°. At 14.9°, the target could appear at one of four equally spaced target locations within each quadrant. At 29.7°, the target could appear at one of three locations within each quadrant. A diagram of the general setup for this and the following experiment can be found in Figure 1.

*Procedure.* At the beginning of each trial, participants fixated on a crosshair at the center of the screen, creating the initial fixation point. Once the crosshair disappeared, the target and distractors appeared on the screen. The experimenter instructed the participants to find the target on each trial and to identify the direction that it pointed by pushing either a left or a right button on a hand-held response box attached to the parallel port of the computer. The participants were instructed to emphasize accuracy over speed because any session with more than 5% incorrect responses would be rerun (a precaution that never became necessary to enforce). The computer recorded the elapsed time between the presentation of the target and the response, or the search time.

The density of distractor stimuli was manipulated per trial in two variables. The presence of distractor stimuli within the local

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target area, a circular field within a 6.5° radius containing the target, was manipulated as *local distractors,* illustrated in Figure 1 as the shaded region. This radius ensured that the local area was within the visual lobe measurements reported by Drury and Clement (1978) and that the local area did not come within 3° of the initial fixation point. The presence of distractor stimuli outside the local target area was manipulated as *global distractors.* Three levels of densities were tested for each distractor variable based on the ratio of distractors to the size of the visual field: 0%, 20%, and 80%. This produced nine distractor density conditions. Sixteen trials were run at each combination of local distractors, global distractors, and target distance, for 288 trials per session, presented in random order.

Three conditions of cue precision were tested. In the accurate or spatially *coincident* condition, the auditory cue was presented at the exact location as the visual target. In the inaccurate or *displaced* condition, the target was displaced ±6° horizontally and vertically from the auditory cue at one of the four possible positions, selected randomly. This displacement amount falls outside of the ranges of error provided by minimum audible angle research (Perrott & Saberi, 1990) and sound localization research (Makous & Middlebrooks, 1990), yet it cues the participant as to the local target area. In the spatially uninformative or *centered* condition, a cue was displayed from the center of the screen, providing no information as to the location of the target. Three sessions were run at each auditory cue condition, with the order randomly determined for each participant. The first session was considered practice and is not included in subsequent analyses.

## Results and Discussion

Target-identification accuracy was high (98%). Using correct trials only, an omnibus four-factor (3 Auditory Cue Precision × 2 Distance × 3 Global Distractors × 3 Local Distractors) repeated-measures analysis of variance was performed on mean search times

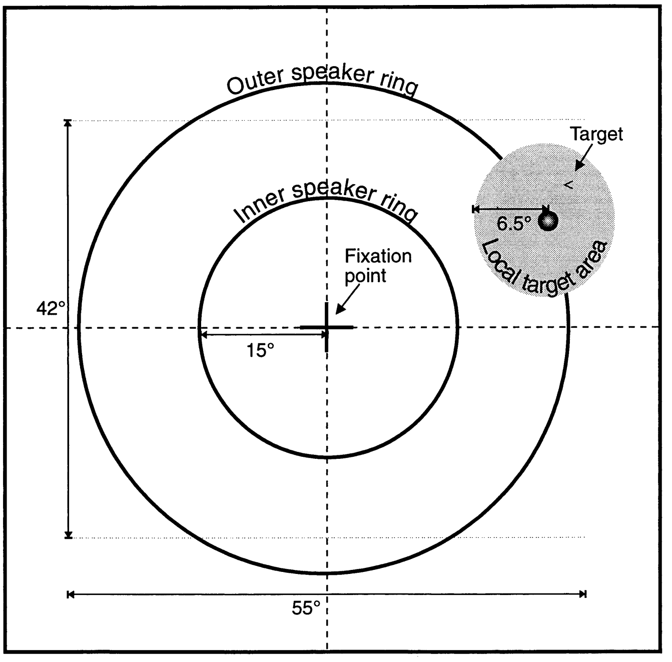


*Figure 1.* Diagram of the speaker setup for both experiments.

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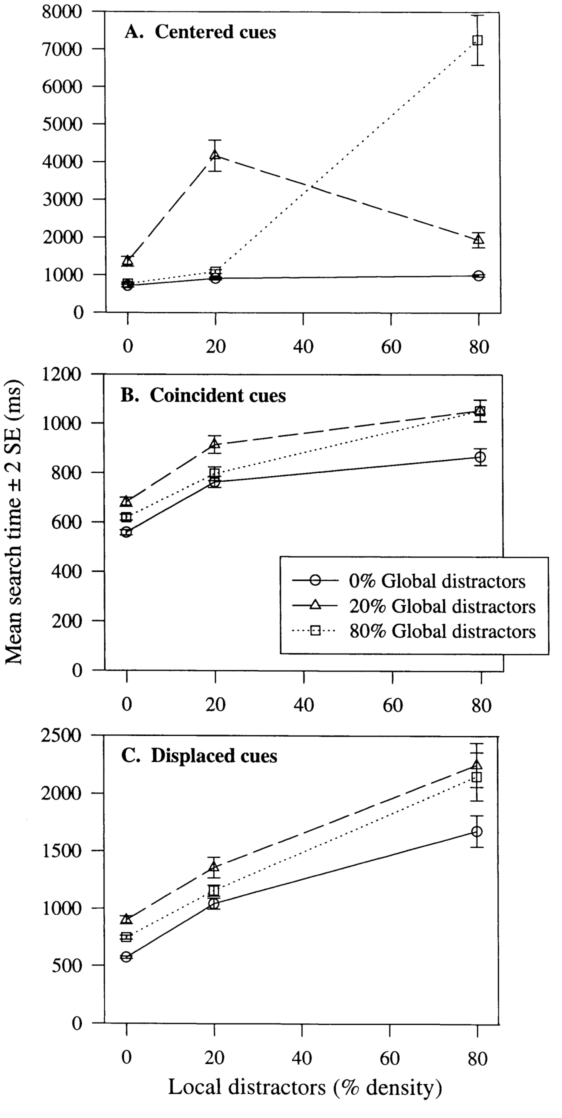


*Figure 2.* Three-way interaction between auditory cue precision and distractor variables on search times, emphasizing changes caused by local distractors.

for each participant and condition. All post hoc analyses were adjusted for a family-wise alpha level of .01.

A three-way interaction between cue precision and both distractor variables was obtained, $F(8, 40) = 31.14$, $p < .0001$, as shown in Figure 2, but the four-way interaction with distance was nonsignificant. In the centered condition, shown in Figure 2A, the effect of local distractors depends on global distractors, a finding supported by post hoc testing of the simple main and interactions effects. Statistically reliable main effects of local and global distractors were obtained, $F(2, 35) = 197.03$, $p < .01$, and $F(2, 35) = 119.96$, $p < .01$, respectively, as well as their interaction, $F(4, 35) = 104.30$, $p < .01$. When distractors were not present outside the local area, or at 0% global distractors, search times increased with increases in density of local distractors, though the effect was small; increasing local distractor density from 0% to 80% raised the mean search time only 140 ms. The most difficult search conditions occurred at equivalent

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densities of global and local distractors (20% local and global distractors, or 80% local and global distractors), which produced search times that were two or three times higher than any other condition.

With equivalent amounts of local and global distractors, visual information about the local target area is unavailable, and search times increase dramatically. In terms of Williams's (1973) model, neither target localization nor target identification information is visually available, and the observer essentially engages in a random search for the target. At 0% global distractors, however, either the target or the local target area is visually provided. Local distractor effects reflect only the identification stage of visual search. When the density of global distractors is greater than 0%, the local area is cued only with nonequivalent densities of local and global distractors (e.g., 80% global and 20% local distractors).

In the spatially coincident condition, increases in the density of local distractors increased the mean search time across all densities of global distractors, as shown in Figure 2B. With coincident cues, the main effects of global and local distractors were reliable, $F(2, 35) = 76.25$, $p < .01$, and $F(2, 35) = 117.62$, $p < .01$, respectively, but the interaction was not, $F(4, 35) = 3.96$. The changes in mean search time occurred with little influence from the amount of global distractors; across densities of global distractors, the mean search times all began within 150 ms of each other at the lowest density of local distractors and within 200 ms of each other at the highest. With spatially coincident cues, then, increases in the density of local distractors always increased mean search times. Increases in the density of global distractors increased mean search times only in comparison with when none were present. That is, once global distractors were present, increases in the amount global distractors did not increase mean search times further.

A similar pattern is present in the spatially displaced condition, shown in Figure 2C. Again, statistically reliable effects of global and local distractors were obtained, $F(2, 35) = 155.97$, $p < .001$, and $F(2, 35) = 29.53$, $p < .001$, respectively, and with an unreliable interaction, $F(4, 35) = 3.11$, $p < .001$. Although the pattern of results is similar to that with the coincident cue, the effects of local and global distractors were greater in the displaced cue condition. For example, in Figure 2B, the slopes of the functions range from 2.92 ms/% local distractors at 0% global distractors to 5.16 ms/% local distractors at 80% global distractors. In Figure 2C, the slopes are 13.1 and 17.4 ms/% local distractors, respectively.

Figure 3 provides another view of the three-way interaction by comparing the effect of auditory cue condition and local distractors at each density of global distractors. At 0% global distractors, the absence of global distractors created a local target area that was always available visually, and any effect of auditory cues should be on the identification stage of visual search. As shown in Figure 3A, search times with coincident cues are on the average 150 ms briefer than with the centered cues. Furthermore, mean search times with displaced cues were longer than with centered cues for local distractors of 20% and 80%. The information provided in the visual arrangement (the cluster of stimuli) was more effective than the displaced auditory cue. These differences at 0% global distractors clearly indicate that auditory spatial cues can affect the identification stage of visual search. A different pattern is evident in Figures 3B and 3C, however. In Figure 3B, search times with displaced cues are briefer than with centered cues at local distractor densities of 0% and 20%, implying that the displaced cue is directing the observer to the local target area more effectively than the visual information. At 80% local distractors, the visual and auditory information are equally effective at drawing the observer's gaze to the local area, because differences in search times are small. Overall, search times are lowest with coincident cues, indicating that target localization and identification are improved. At 80% global distractors, shown in Figure 3C, search times with displaced cues are lower than with centered cues only at 80% local distractors. When the target's local area is unavailable visually, the displaced cue is more effective than a spatially noninformative cue.

In summary, the results of this experiment suggest that auditory spatial cues can affect

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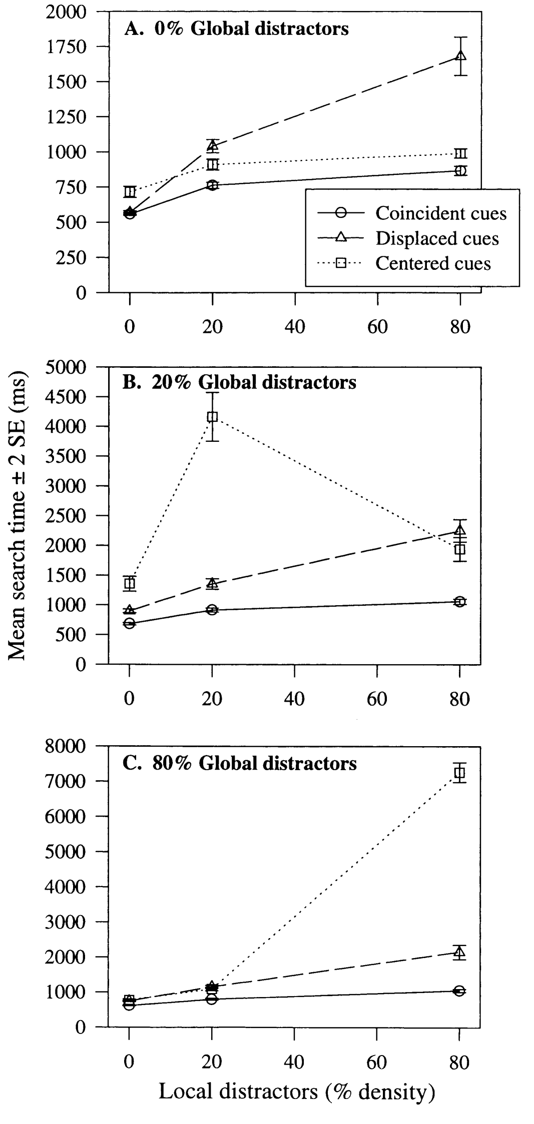


*Figure 3.* The same three-way interaction shown in Figure 2, emphasizing the influence of global distractors.

target localization and target identification. When auditory spatial cues pointed to the exact location of the target, search times were minimally affected by local as well as global distractors. In the displaced condition, search performance was facilitated only when the density combination of local and global distractors provided little or no information about the target's local area. However, in two instances (0% global distractors and 20% local distractors as shown in Figure 3A, and 20% global distractors and 80% local distractors as shown in Figure 3B) search times with displaced cues were longer on average than with centered cues, suggesting that our observers would have found the target faster if they had ignored the displaced auditory cue and relied on the visual information for the local target area in these conditions.

An inability to ignore the auditory cue would imply an exogenous cuing mechanism. In this experiment, sessions consisted of a constant, reliable auditory cue condition and variable visual information. Thus, the auditory

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cue was reliable and the visual cues were not. In order to determine how the reliability of the cues affected visual search performance, a second experiment was conducted in which the reliability was reversed: The auditory cue conditions varied within a session, and the distractor density combinations were constant. Finally, we ran one additional session in which both auditory and visual information varied randomly within a session.

## EXPERIMENT 2: UNRELIABLE AUDITORY CUES

### Method

*Participants.* Four students, all with normal hearing and normal or corrected-to-normal vision, served as observers. Two had served in Experiment 1, and two had no previous experience in visual search experiments.

*Apparatus.* The apparatus and visual and auditory stimuli were the same as Experiment 1.

*Procedure.* Three densities of global and local distractors (0%, 20%, and 80%) and three auditory cuing conditions (coincident, displaced, and centered) were again tested. However, within a session each auditory cuing condition was presented 30 times at each distance (14.9° and 29.7°) in random order, creating a session of 180 trials. Three sessions were run at each of nine density combinations of global and local distractors, with the first session considered as practice. In these trial blocks, visual information about target location was reliable but the information contained in the auditory cue was unreliable. That is, at the beginning of each trial, participants did not know whether the auditory cue signaled the exact location, the local target area, or the center of the search field. Participants were again instructed to locate and identify the visual target as quickly as possible, but accuracy was emphasized over speed.

After all nine combinations were completed, an additional three sessions were run. In this trial block, the auditory cue condition, local distractors, and global distractors varied within a session; both visual and auditory information about the location of the target was unreliable. Participants did not know at the beginning of a trial whether the visual or auditory stimulus provided information about the target's location. Twelve trials were run at each of the 27 combinations, creating a session of 324 trials. In order to keep the number of trials within a session reasonable, target distance varied randomly for this block only.

### Results and Discussion

The mean search time was computed for each participant and condition, and two repeated-measures analyses of variance (ANOVAs) were computed: a four-factor (3 Auditory Cue Precision × 2 Distance × 3 Global Distractors × 3 Local Distractors) repeated-measures ANOVA for the unreliable auditory-reliable visual information trial blocks and a three-factor (3 Auditory Cue Precision × 3 Global Distractors × 3 Local Distractors) ANOVA for the unreliable auditory-unreliable visual trial blocks. A reliable three-way interaction among auditory cue condition, global distractors, and local distractors was obtained in each analysis: unreliable auditory-reliable visual, $F(8, 24) = 62.95$, $p < .0001$; unreliable auditory-unreliable visual, $F(8, 24) = 21.4$, $p < .0001$. The interactions are shown in Figure 4. At 0% global distractors, the benefit of coincident cue is maximal at 20% local distractors when the visual information is reliable (Figure 4A), presumably because the visual information about the target or local target area is least salient here. At local distractor densities of 0% and 80%, the benefit of auditory spatial cues is only 40 ms. When both auditory and visual information is unreliable (Figure 4D), the difference between the coincident and centered cues is more in line with that obtained in Experiment 1. However, the difference between search latencies in the coincident-cue and displaced-cue conditions increased with increases in local distractors. These effects were obtained when the visual information was reliable (Figure 4A) and when the visual information was unreliable (Figure 4B).

The results at global distractors of 20% and 80% are similar to those obtained in Experiment 1. Coincident cues produced the briefest search times, and these were least affected by local distractors. The displaced cue condition lowered search latencies only when the densities of local and global distractors

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were equivalent (20% global and local distractors shown in Figures 4B and 4E, and 80% global and local distractors shown in Figures 4C and 4F). When the distractor density combinations visually indicated the local target area – that is, in any nonequivalent distractor densities such as 0% to 20%, 0% to 80%, 20% to 80%, and 80% to 20% – search latencies were higher with displaced cues than with centered cues, which also agrees with the results of Experiment 1. This further suggests that our participants were unable to ignore the auditory stimulus, because participants in the first series did have reliable information about the visual information provided on each trial. Nevertheless, search latencies in the displaced cue condition were always higher than in the centered cue

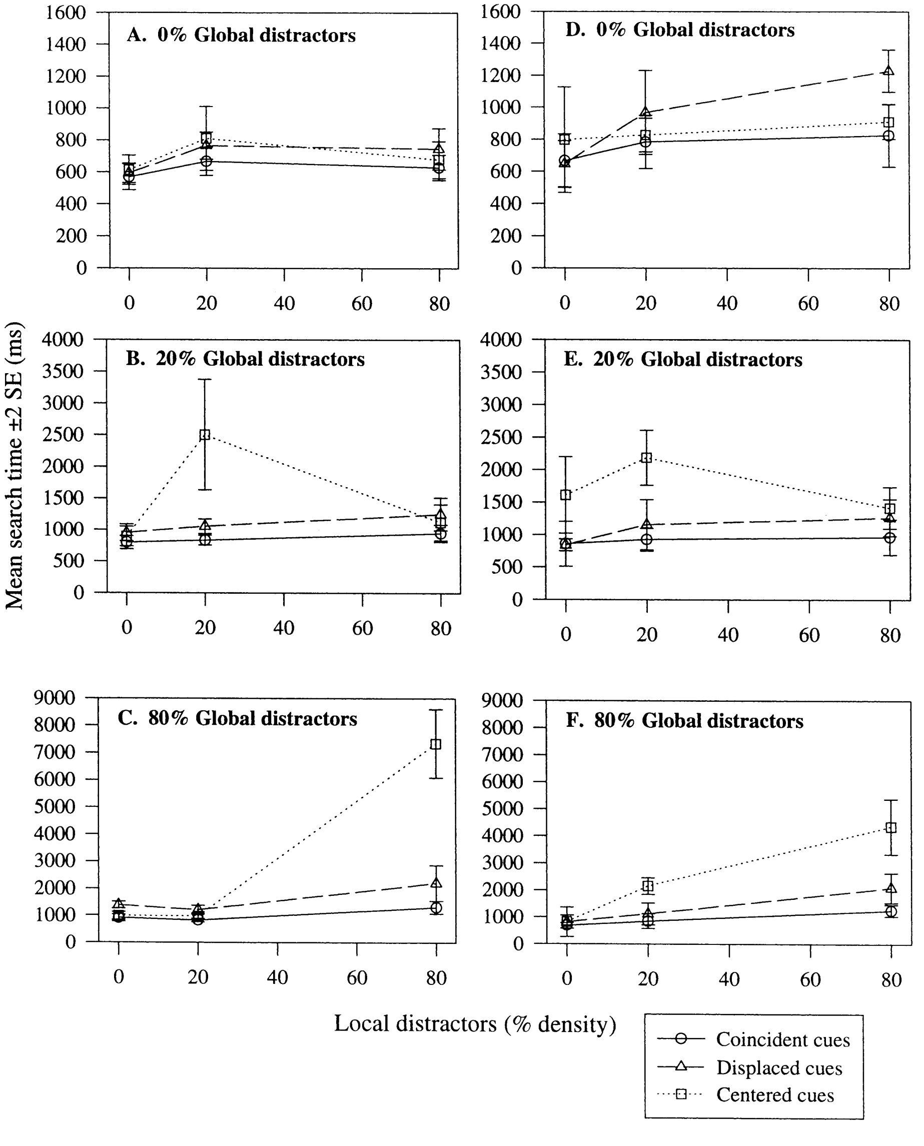


*Figure 4.* Three-way interactions between auditory cue precision and distractor variables on search times for reliable and unreliable visual information in Experiment 2. Reliable visual information data are shown in the left panels.

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conditions for the global-local combinations noted previously. This effect was also obtained when both auditory and visual target information was varied within a session.

Figure 5 compares the effectiveness of the displaced and coincident auditory cue conditions under three conditions of reliability: reliable auditory-unreliable visual information from Experiment 1, and unreliable auditory-reliable visual and unreliable auditory-unreliable visual information from Experiment 2. The most important pattern that emerges from these figures is the ineffectiveness of cue reliability in the coincident cue conditions. In Figures 5A and 5B these coincident cue functions overlap. Cue reliability affected neither search latencies nor the effect of local distractors on search latencies. Only in the most

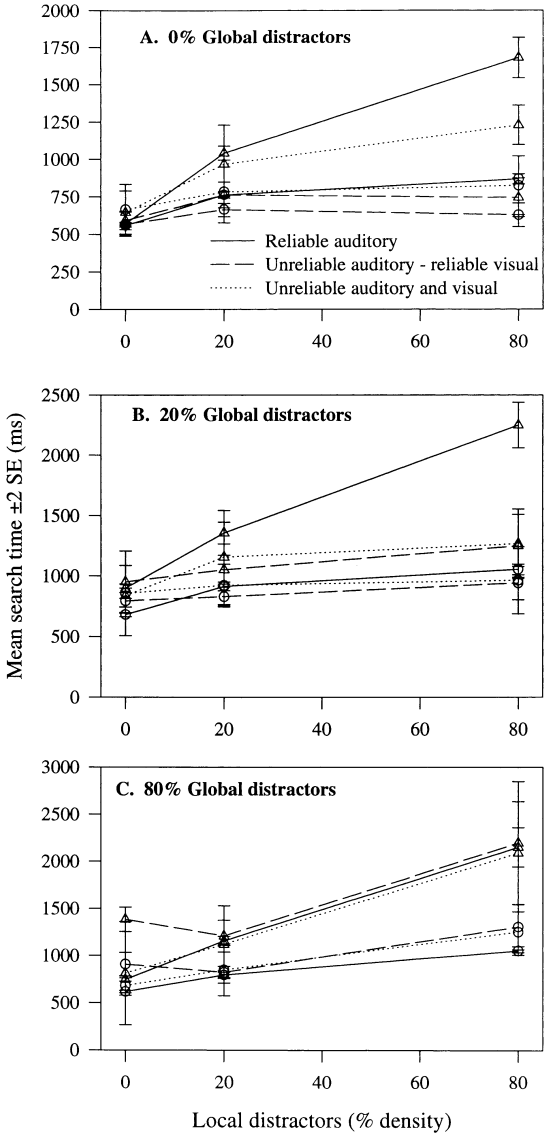


*Figure 5.* Comparisons of the effects of coincident and displaced auditory cues on search times from both experiments, highlighting the lack of effect for auditory cue reliability with coincident cues.

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visually demanding condition, 80% global and local distractors, shown in Figure 5C, is there an advantage of a reliable coincident cue. However, the effectiveness of the displaced cue depended on cue reliability. In Figures 5A and 5B, the longest search latencies were obtained when the displaced cue was reliable. Furthermore, the slope of the reliably displaced cue condition was higher than in either unreliable auditory cue condition (13.1 ms/% vs. 9.0 ms/% and 7.4 ms/% in Figure 5A; 16.5 ms/% vs. 4.1 ms/% and 5.5 ms/% in Figure 5B). Reliability did not improve performance with displaced cues; rather, participants performed most poorly when the displaced cue was reliable. At 80% global distractors, no effects of reliability on the displaced cue condition are evident.

## GENERAL DISCUSSION

Two main findings emerge from these experiments. First, auditory spatial cuing can facilitate both the localization and identification stages of visual search performance, an effect that varies in size by characteristics of the visual search field. Second, when the auditory spatial cue is spatially exact, cue reliability has no effect. When the cue is slightly displaced from the target, reliability can affect search performance.

Highly precise or exact auditory spatial cues reduce the time required to locate and identify a visual target. Our results extend the finding that the benefit of an auditory spatial cue relies on the presence of distractors (e.g., Perrott et al., 1991) by examining the effectiveness of auditory spatial cuing on target localization and target identification separately and simultaneously. Partitioning visual search into a preliminary stage of finding the local target area followed by a stage of identifying the target (Williams, 1973) allowed for a closer examination of how auditory spatial facilitation works and under which visual demands it works best. The benefits of auditory spatial cues on the localization stage can be seen in Figures 2 and 3. For example, at 20% global distractors and 0% local distractors, once the local target area is reached, target identification should occur quickly because only the target is present. At this condition, the mean search times were 680 ms faster in the coincident cue than with the centered cue condition, as shown in Figure 2B. Of course, with these distractor densities, visual information about the local target area is available. When the distractor density combination produced no visual cue as to the local target area (e.g., 20% global and local distractors in Figure 2B), search times were reduced 3200 ms in the coincident cue condition and 2800 ms in the displaced cue condition. Thus, auditory spatial cuing can facilitate target localization, with the size of the benefit dependent on the amount of visual information available.

The effectiveness of auditory spatial cues in the identification stage of visual search can be seen in Figure 3A, when no global distractors were present. In this condition either the target or local target area was always available visually, yet search latencies in the coincident cue condition were, on average, 150 ms lower than with the centered cue condition. This reduction must be attributed to an improvement in the identification stage of visual search. That displaced cues degraded performance at 0% global distractors is further evidence of a facilitatory effect on target identification. The displaced cues did signal the local target area, yet the mean search times and the effect of local distractors were more dramatic in the displaced cue condition. As shown in Figures 2B and 2C, the slopes of the functions in the displaced cue condition (13–17 ms/% local density) were much higher than in the coincident cue condition (2–5 ms/% local density). Thus, accuracy of the auditory spatial cue within the local target area can affect visual search performance. It appears from our data that auditory spatial cuing not only signals the general target area but also enhances subsequent target identification. Because the radius of the local target area was 6.5°, once the observer was focused on this area, all targets were in the parafoveal region of the eye. The 1°-wide target should have been easily detectable, yet coincident auditory cues reduced search times by 150 ms, a finding consistent with previous research (e.g., Perrott et al., 1990, 1991; Strybel &

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Perrott, 1993) that found facilitatory effects for targets at or near the initial fixation point.

Auditory facilitation of target localization and identification was obtained whether the accuracy of the cue was reliable within a session or varied between trials. That is, the effectiveness of coincident auditory cues obtained in Experiment 1, in which cue precision was constant throughout an experimental session but visual target information varied, was also obtained in Experiment 2, in which the situation was reversed (auditory cue precision varied and visual information was constant within a session). The ineffectiveness of cue reliability implies an exogenous cuing mechanism. An exogenous effect is also suggested in those distractor density combinations that visually cued the local target area (e.g., 0%–20%, 0%–80%, 20%–80%, 80%–20%). In these conditions, search latencies were higher with displaced cues than with centered cues, suggesting that our participants were unable to ignore the auditory stimulus. Of course, in Experiment 1, participants were unable to predict whether the visual information would cue the local area, but in the first series of Experiment 2, participants were aware of the visual information provided on each trial. Nevertheless, search latencies in the displaced cue condition were always higher than in the centered cue conditions for the distractor density combinations noted previously. This effect was also obtained when both auditory and visual target information was varied within a session.

This effect might be similar to that obtained by Frens, Van Opstal, and Van der Willigen (1995), who measured the accuracy and latency of eye saccades to a visual target accompanied by a broadband noise burst either spatially coincident with the target or displaced by some amount. Here the auditory stimulus did not reliably cue the target: Participants were instructed to ignore it. Saccadic latencies were reduced by 35 ms on the average when the auditory stimulus was coincident with the visual target. Furthermore, when the auditory stimulus was displaced from the target, the size of the latency reduction was reduced. Frens et al. concluded that eye saccades are directed toward a weighted-average position of the auditory and visual stimulus with stimulus size and intensity the weighting factors. If our participants responded in this fashion, it would suggest that the initial eye saccade to the local target area was less accurate with the displaced cue than with the visual information alone in the centered cue condition. Of course, confirmation of this explanation requires that eye and head movements be monitored during the visual search task.

## DESIGN IMPLICATIONS

The required precision of auditory spatial cues depends on the visual demands imposed on the operator engaged in the visual search task and the time demands of the task. If the search field contains no other targets, an auditory spatial cue will reduce search latencies by a small amount. For example, in Experiment 1, the mean search latency at 0% local and global distractors was reduced by 150 ms with a coincident auditory cue and 144 ms with the displaced cue. Thus, if the entire target area is free of distractors, increasing the precision beyond 6.5° (the size of the local target area) may not improve performance. This may account for the failure of Perrott et al. (1995) to find large decrements in search performance when either simulated 3D or 2D cues were used. If visual distractors are present but lie outside the local target area, cuing the local target area may be all that is necessary. As mentioned previously, when the local area was without distractors, the difference in mean search times between coincident and displaced cues was small.

However, when visual distractors are present in the local target area, precision is critical. Small displacements (±6.5°) can significantly impair search performance. In fact, our results suggest that if the cue is in error and accurate visual information is available, it may be better to turn off the cue, because of our participants' inability to ignore the displaced cue and attend to the visual information about the target. Furthermore, small target-cue separations may be more detrimental than large separations because in many conditions, search times were lower in the centered cue condition than in the displaced cue condition.

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In the centered cue condition, an auditory stimulus was available, but it would have been at least 15° away from the target.

Frens et al. (1995) suggested that when an eye saccade trajectory is computed, the weight given to the position of the auditory stimulus is lessened as separation increases. This implies that in a highly cluttered local target area, small errors in the auditory spatial cue would be weighted more heavily and interfere with target identification more than would large errors (assuming the operator has obtained the local target area). Of course, if the local area is not available visually, the benefit of displaced cues in signaling the local area would probably outweigh the interference with target identification within the local area. The greatest benefit of auditory spatial facilitation, however, seems to lie in target localization, an inference that is unsurprising given the greater acuity of the human visual system. Designers of virtual environments will need to weigh the costs and benefits of improvements in auditory 3D precision against the use of visual cues to the target.

Further complicating this issue is the operator's knowledge of cue precision. Note in Figure 4 that the greatest "cost" of displaced auditory cues occurred when the displacement was reliable and visual information unreliable. Participants may have used a less-than-optimal strategy in this case because when they could not determine cue accuracy in Experiment 2, search latency was affected less. Thus, designers of virtual environments will need to have an understanding of the typical visual environment, task speed requirements, operator training/experience, and auditory lag and/or imprecision created by the 3D auditory system in order to decide the best way to implement 3D auditory cues.

In summary, the precision of auditory spatial cues depends on the presence of distractors in the overall search field and in the local area surrounding the target. These results are restricted to targets in the frontal visual field (±30°), where visual cues as to the target or local target area are more likely to be present. As the search field increases, the auditory spatial cue will play a more important role (e.g., Perrott et al., 1995; Strybel et al., 1995). Precision requirements have not been evaluated for search in the periphery, however.

## REFERENCES


Begault, D. R. (1993). Head-up auditory displays for traffic collision avoidance system advisories: A preliminary investigation. *Human Factors, 35,* 707–717.

Begault, D. R. (1995). Head-up auditory display research at NASA Ames Research Center. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 114–118). Santa Monica, CA: Human Factors and Ergonomics Society.

Doll, T. J., & Hanna, T. E. (1997). Directional cuing effects in auditory recognition. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and spatial hearing in real and virtual environments* (pp. 377–397). Mahwah, NJ: Erlbaum.

Drury, C. G., & Clement, M. R. (1978). The effect of area, density, and number of background characters on visual search. *Human Factors, 20,* 597–602.

Fisher, H. G., & Freedman, S. J. (1968). The role of the pinna in auditory localization. *Journal of Auditory Research, 8,* 15–26.

Frens, M. A., Van Opstal, A. J., & Van der Willigen, R. F. (1995). Spatial and temporal factors determine auditory-visual interaction in human saccadic eye movements. *Perception and Psychophysics, 57,* 802–816.

Fujawa, G. E., & Strybel, T. Z. (1997). The effects of cue informativeness and signal amplitude on auditory spatial facilitation of visual performance. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting* (pp. 556–560). Santa Monica, CA: Human Factors and Ergonomics Society.

Makous, J. C., & Middlebrooks, J. C. (1990). Two-dimensional sound localization by human listeners. *Journal of the Acoustical Society of America, 87,* 2188–2210.

McKinley, R. L., D'Angelo, W. R., Haas, M. W., Perrott, D. R., Nelson, W. T., Hettinger, L. J., & Brickman, B. J. (1995). An initial study of the effects of three-dimensional auditory cueing on visual target detection. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 119–123). Santa Monica, CA: Human Factors and Ergonomics Society.

McKinley, R. L., & Ericson, M. A. (1997). Flight demonstration of a 3-D auditory display. In R. H. Gilkey & T. R. Anderson (Eds.), *Binaural and spatial hearing in real and virtual environments* (pp. 683–699). Mahwah, NJ: Erlbaum.

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology, 42,* 135–159.

Perrott, D. R., Cisneros, J., McKinley, R. L., & D'Angelo, W. R. (1995). Aurally aided detection and identification of visual targets. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 104–108). Santa Monica, CA: Human Factors and Ergonomics Society.

Perrott, D. R., Cisneros, J., McKinley, R. L., & D'Angelo, W. R. (1996). Aurally aided visual search under virtual and free-field listening conditions. *Human Factors, 38,* 702–715.

Perrott, D. R., & Saberi, K. (1990). Minimum audible angle thresholds for sources varying in both elevation and azimuth. *Journal of the Acoustic Society of America, 87,* 1728–1731.

Perrott, D. R., Saberi, K., Brown, K., & Strybel, T. Z. (1990). Auditory psychomotor coordination and visual search performance. *Perception and Psychophysics, 48,* 214–226.

Perrott, D. R., Sadralodabai, T., Saberi, K., & Strybel, T. Z. (1991). Aurally aided visual search in the central visual field: Effects of visual load and visual enhancement of the target. *Human Factors, 33,* 389–400.

Strybel, T. Z., Boucher, J. M., Fujawa, G. E., & Volp, C. S. (1995). Auditory spatial cueing in visual search tasks: Effects of amplitude, contrast and duration. In *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting* (pp. 109–113). Santa Monica, CA: Human Factors and Ergonomics Society.


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Strybel, T. Z., & Perrott, D. R. (1993, November). *Auditory facilitation of visual search performance: Serial or parallel processing.* Presented at the 34th Annual Meeting of the Psychonomic Society, Washington, D.C.

Wenzel, E. M., Wightman, F. L., & Foster, S. H. (1988). A virtual display system for conveying three-dimensional acoustic information. In *Proceedings of the Human Factors Society 32nd Annual Meeting* (pp. 86–90). Santa Monica, CA: Human Factors and Ergonomics Society.

Wightman, F., L., & Kistler, D. J. (1989). Headphone simulation of free-field listening: I. Stimulus synthesis. *Journal of the Acoustical Society of America, 85,* 858–867.

Williams, L. G. (1973). Studies of extrafoveal discrimination and detection. In Committee on Vision Division of Behavioral Sciences and National Research Council (Eds.), *Visual search* (pp. 77–92). Washington, DC: National Academy of Sciences.

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