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Objective: Our aim was to investigate how the congruency between visual displays and auditory cues affects performance on various spatial tasks. **Background:** Previous studies have demonstrated that spatial auditory cues, when combined with visual displays, can enhance performance and decrease workload. However, this facilitation was achieved only when auditory cues shared a common reference frame (RF) with the visual display. In complex and dynamic environments, such as airborne search and rescue (SAR), it is often difficult to ensure such congruency. **Method:** In a simulated SAR operation, participants performed three spatial tasks: target search, target localization, and target recall. The interface consisted of the camera view of the terrain from the aircraft-mounted sensor, a map of the area flown over, a joystick that controlled the sensor, and a mouse. Auditory cues were used to indicate target location. While flying in the scenario, participants searched for targets, identified their locations in one of two coordinate systems, and memorized their location relative to the terrain layout. **Results:** Congruent cues produced the fastest and most accurate performance. Performance advantages were observed even with incongruent cues relative to neutral cues, and egocentric cues were more effective than exocentric cues. **Conclusion:** Although the congruent cues are most effective, in cases in which the same cue is used across spatial tasks, egocentric cues are a better choice than exocentric cues. **Application:** Egocentric auditory cues should be used in display design for tasks that involve RF transformations, such as SAR, air traffic control, and unmanned aerial vehicle operations.

INTRODUCTION

In complex and dynamic environments, such as search-and-rescue (SAR) missions, operators carry out multiple tasks concurrently using various sources of information. This places a strain on the operator's cognitive resources, which can result in cognitive overload and an increase in errors. These risks can be reduced by presenting necessary information in a manner that is congruent with the information-processing demands of tasks that the operator needs to perform.

Researchers have repeatedly demonstrated that the effectiveness of different display formats is task dependent (Lamb & Hollands, 2005; Olmos, Wickens, & Chudy, 2000; St. John, Cowen, Smallman, & Oonk, 2001; Wickens, 1999; Wickens, Liang, Prevett, & Olmos, 1996; Wickens & Prevett, 1995). For example, spatial information can be represented using two-dimensional (2-D) or three-dimensional (3-D) perspectives' or using egocentric or exocentric reference frames (RFs). The egocentric RF is defined in terms of left-right, above-below, and near-far directions; the exocentric RF, on the other hand, is defined in world-referenced terms, such as cardinal directions (north, south, east, and west; Wickens, 1999).

It has been shown that navigation and flight path control are performed better with more egocentric 3-D perspective displays and aircraft-up maps, whereas situation awareness and long-term retention of terrain features are facilitated by more exocentric 2-D perspectives and north-up maps (Lamb & Hollands, 2005; Olmos

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et al., 2000; Wickens et al., 1996; Wickens & Prevett, 1995). In complex environments such as SAR, however, task demands can be diverse, and a single display may be suitable for some tasks but not others.

Researchers have shown that the use of auditory spatial cues can improve an operator's performance (Barfield, Cohen, & Rosenberg, 1997; Begault, 1993; Bronkhorst, Veltman, & Breda, 1996; McKinley & Ericson, 1997). Begault (1993) demonstrated faster target acquisition for commercial airline crew when a verbal cue was presented with 3-D audio using two earpieces, compared with a standard one-ear presentation. Similarly, McKinley and Ericson (1997) found improved speech intelligibility, better spatial awareness, decreased mental workload and faster target acquisition when spatial auditory cues were used relative to the standard visual heads-up displays alone or verbal cues presented to one ear only.In both studies, 3-D auditory displays were used to give the participant the illusion that the sound was emanating from an external location (the signals simulated acoustic effects of the listener's shoulders, head, and external ear using head-related transfer functions). In addition, visual displays and auditory cues in both studies used a common, egocentric RF.

A pair of studies of particular interest for our experiment specifically examined how correspondence (or lack thereof) between visual and auditory RFs affected performance. Bronkhorst et al. (1996) examined the effectiveness of a radar visual display and 3-D auditory cues in conveying directional information in a flight simulation experiment. The task involved locating and trailing a target aircraft that suddenly disappeared and reemerged at an unknown position. When at short range, the target position was displayed on an "out-the-window" 3-D view showing the ground airstrip, and a 3-D tactical display indicated target position at all distances within a limited field of view.

These 3-D displays were augmented by a bird's-eye-view radar display, which indicated whether the target was above or below the observer's aircraft, and/or an auditory spatial cue, which generated a warning sound from the direction of the target relative to the participant. Results showed a reduction in search time with both the radar display and the auditory cue compared with the tactical display alone (Bronkhorst et al., 1996). In addition, there was a further reduction in the search time in the combined condition relative to the radar display alone; there was no difference between the auditory cue and combined display conditions. Bronkhorst et al. (1996) attributed performance improvements with the auditory cues to a common egocentric RF between the auditory cues and the tactical display.

In the second study, Barfield et al. (1997) also compared auditory, visual, and combined auditory-visual displays for spatial localization judgments. The visual condition required judging the relative azimuth and elevation of a visual target relative to a reference object using a perspective view; the auditory condition required judging the azimuth and elevation of a 3-D sound source with respect to the listener. In the combined auditory-visual condition, the azimuth and elevation of the visual target were the same as those of the sound cue. The results demonstrated no difference between the visual perspective and combined displays, and the worst performance was obtained with auditory display alone. The lack of correspondence between the auditory cue's egocentric RF and the visual display's object-centered RF required additional spatial alignment, which caused the auditory cue to be ignored in the combined condition (Barfield et al., 1997).

The findings from the two studies emphasize the importance of RF congruency between auditory cues and visual displays. In the Bronkhorst et al. (1996) study, the auditory and visual reference frames were in alignment, and the presence of auditory cues improved performance compared with the condition with visual displays only. In the Barfield et al. (1997) study, the auditory and visual RFs were not in alignment, and the presence of auditory cues did not improve performance relative to visual displays alone. In such cases, the RFs may need to be mentally aligned to perform the tasks successfully, which requires time, increases the probability of error, and may require additional cognitive resources (Barfield et al., 1997).

The RF misalignment across displays poses challenges for the design of bimodal interfaces for complex and dynamic environments. It is often difficult to ensure continuous congruency between auditory cues and visual displays over time. Hence, it is important to evaluate different display configurations to determine which will be most effective across tasks.

The current study examined how RF congruency between visual displays and auditory cues affects performance on various spatial tasks in a simulated SAR mission. The SAR domain is well suited to this effort, as it involves multiple spatial tasks that are performed either concurrently or in close succession (Keillor, Hodges, Perlin, Ivanovic, & Hollands, 2002).

In our experiment, participants used a sensor system to search for crashed aircraft and identify their location in the azimuth relative either to north or to the sensor. This represents an abstraction of the current concept of operations for such sensor systems, in which the sensor operator would be provided with gross positional information based on the emergency locator transmitter (ELT) signal by the air navigator (*National SAR Manual*, 1998). This situation would require the SAR operator to integrate the positional information with *both* personal and system RFs, because the sensor system is designed to be independent of the flight management system.

It is worth noting that this type of task is not unique to SAR operations; the operator of an uninhabited aerial vehicle may face similar RF alignment challenges when searching for targets and reporting target details to mission command (Dixon & Wickens, 2006).

In addition, although ELTs are designed to signal an aircraft crash and provide positional information that can be captured by satellites, there are many reported incidents of malfunction that, coupled with a high false alarm rate, highlight their limited effectiveness and ease of use (Trudell & Dreibelbis, 1990). Until such time that the technology is sufficiently reliable and affordable, efforts should be made to design a display configuration that will assist the SAR operator in integrating positional information across different RFs.

In our simulation, the sensor system consisted of two visual displays: an egocentric sensor view and a map display. Auditory cues simulating gross positional information provided to the aircraft based on the output of an ELT signal were used to represent target location in either an egocentric or an exocentric coordinate system. Once the target was found, the participant used one of two visual response displays—egocentric or exocentric—to indicate target location. The auditory cue RF was thus congruent with some displays but incongruent with others.

In contrast to the Bronkhorst at al. (1996) and Barfield et al. (1997) studies, we compared congruent and incongruent auditory cues with a neutral condition, in which no target location information was provided by the cue, instead of using a combined display condition with redundant visual cues. We hypothesized that better performance would be obtained in congruent than in incongruent conditions; that is, we should expect to observe *congruency effects*. In addition, because continuous congruency between cues and displays across tasks cannot always be ensured in real-world SAR operations, we examined whether incongruent cues would produce any performance benefits relative to a neutral control condition and whether these benefits would vary across the task sequence.

METHOD

Participants

Participants were 12 male and 12 female volunteers between the ages of 18 and 55 with self-reported normal or corrected-to-normal vision; they were paid for their participation. All were required to pass a sound localization test that involved pointing to the loudspeaker from which the sound cue was randomly presented. The pass criterion adopted was 75% accuracy (18 of 24 correct).

Simulation

In the simulated SAR mission, participants flew at 300 knots (154.33 m/s) through a 5,600- by 6,000-m virtual terrain model at an altitude of 300 m on a fixed creeping-line search path. The creeping-line pattern involved flying east and west and crossing the virtual terrain eight times on each flight. Each of the eight legs of the flight plan was 3,000 m long, and the turns were made sufficiently long (600 m) such that the area under the east and west legs was covered with the least amount of overlap. The flight was automated, and participants had no control of aircraft heading.

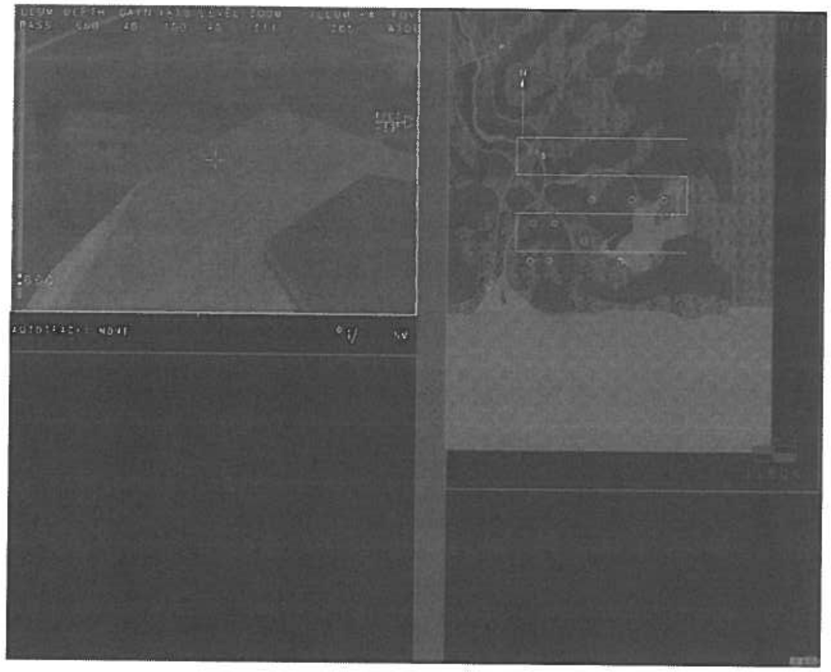

Figure 1. Simulator interface during flight depicting the sensor view and the north-up map. The white line represents the flight plan and the white circles are the examples of target locations. Neither were visible in the actual scenarios.

The search scenarios were presented on a 21-inch (533 mm) IBM P275 CRT monitor powered by a Silicon Graphics Octane computer at a 30-Hz refresh rate. The simulator display consisted of the egocentric sensor view of the terrain and a map of the entire area (see Figure 1). Participants moved the sensor clockwise or counterclockwise by pushing the joystick to the right or left, respectively. The sensor pitch was locked at −30° below the horizontal axis of the aircraft, and possible motion was limited to a 360° arc in the azimuth around the aircraft. The rate of rotation was proportional to the amount of joystick deflection, with a maximum rate of 150°/s at full deflection. This setup resembles the systematic search patterns recommended in the *National SAR Manual* (1988), which were designed to increase search effectiveness and improve search area coverage.

The map contained a north indicator and an aircraft symbol indicating the flight direction. The map was either north up (exocentric) or aircraft up (egocentric). The two maps differed in how they represented the change in flight direction. In the north-up map condition, the change in flight direction was illustrated by a rotating aircraft on a fixed (north-up) view of the terrain. In the aircraft-up map condition, the map rotated around a static aircraft pointing up when the flight direction changed.

Auditory cues were presented through eight loudspeakers (Tapco two-way monitors) arranged around the seated participant at ear height in a circular array (approximately 1-m radius) and at 45° separation (at 22.5°, 67.5°, 112.5°, 157.5°, 202.5°, 247.5°, 292.5°, and 337.5° with respect to the participant's viewpoint). This loudspeaker arrangement was chosen for two reasons: (a) Speaker positions needed to be in the same plane and symmetrical around both the midline and interaural axis to maintain congruency between location of the auditory cue and the visual target, and (b) previous research has shown that localization acuity close to the midline or interaural axis is impaired for sounds separated by less than 30° (Abel, Giguere, Consoli, & Papsin, 1999). The auditory cue was a 500-ms, 60-dBA white noise sample. Several sound measurements were taken for each speaker, with the meter located approximately at ear level in the

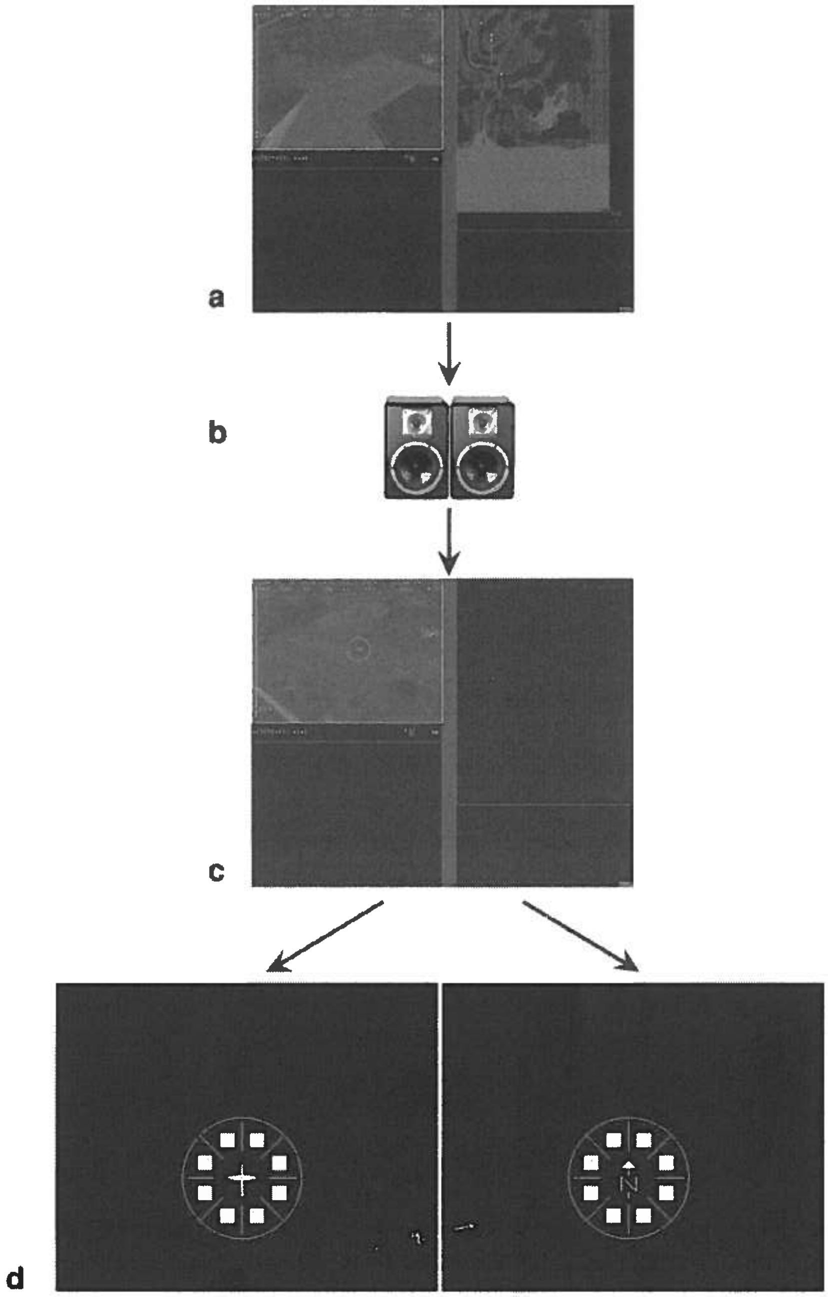

Figure 2. Visual displays and the sequence of events in the experimental scenario. (a) Simulator interface appears during flight. (b) Auditory cue initiates target search. (c) The map is removed from the display during target search (the target is depicted within the white circle, not visible in the actual scenario). (d) Upon finding the target, the participant sees the egocentric (aircraft icon in center) or the exocentric (*N* indicator in center) response display for the target localization task.

center of the array, to ensure that sound of the same intensity was emitted from all speakers.

The tasks required participants to find crashed A-10 aircraft (*target search task*), identify target locations using an egocentric or an exocentric coordinate system (*target localization task*), and memorize the aircraft's locations relative to the terrain layout (*target recall task*). Figure 2 depicts the target as it appeared on the terrain (within the white circle). Target location was indicated by the auditory cue emitted from one of the eight loudspeakers. In the egocentric auditory condition, participants were told that the cue indicated target location in the left, right, front, or back direction; in the exocentric auditory condition, the cue indicated target location in the north, south, east, or west direction. Neutral auditory cues were emitted from all loudspeakers simultaneously. Thus, these cues indicated the appearance of a target within the sensor range but did not indicate target location. Participants could consult the map (north up or aircraft up) to determine the current flight direction.

Visual response displays were used for the target localization tasks (see Figure 2). These depicted a circular array of boxes placed at equal distances from each other. The egocentric response display had an aircraft icon in the center. The exocentric response display had a north indicator in the center. The mouse button was used to indicate target location on response displays.

The search path covered a different terrain area for each experimental scenario. The locations of 32 targets were different across scenarios, with the constraint that there were 2 targets for each flight direction and loudspeaker position, generating two sets of 16 targets in total. One set of targets was used for the egocentric localization trials and the other for the exocentric localization trials. No target was placed on north or south legs, and east and west legs were separated so that the search areas did not overlap. This was done to ensure that there were only 8 possible target locations at any given time.

The experiment took place in a quiet room with normal temperature and dimmed lighting to enhance the sensor display contrast.

Procedure

Before each experimental scenario, participants completed a practice trial that was a shorter version of the experimental scenario. The experimenter provided the necessary instructions and answered questions about the tasks.

Each experimental scenario started with the aircraft in flight, with both sensor and map display visible, and the sensor direction was locked to the aircraft heading (to prevent participants from detecting targets before the sound cue was presented). During flight, participants were told to consult the map to determine flight direction and to monitor both the sensor and the map display to get a good sense of the terrain layout.

Target search task. The target search task was initiated by an auditory cue. Immediately after the cue was presented, the flight was paused and the map removed from the display. Participants were instructed to use the joystick to move the sensor in the direction indicated by the cue and search for the target. The search was terminated once the participants pressed the joystick button to indicate that the target had been detected.

Target localization task. After the target had been detected, the search display was replaced by one of two response displays for the target localization task. If shown the egocentric response display, the participant indicated target location in aircraft-up coordinates by clicking on the appropriate box in the circular array using a mouse (see Figure 2). If the exocentric response display was shown, the participant indicated target location in north-up coordinates.

The order of response display type was randomized across trials with the constraint that an equal number of egocentric and exocentric displays were presented. Participants were unaware ahead of time which display they would use to make their response. This procedure prevented participants from anticipating how they would respond and ensured that RF alignment was completed immediately before the response was made.

Speed and accuracy were declared equally important in this task. Once the target location response was collected, the flight resumed until an auditory cue signaled the search for another target. Figure 2 depicts the visual displays and sequence of events in the experimental scenario.

Target recall task. The experimental scenario was replayed for the target recall task, this time with no cues or targets present. The timing was identical to that in the original scenario. Both the sensor view and the map were continuously available. Instead of searching for targets in the sensor view, participants were instructed to find the former target locations using the joystick

TABLE 1. Congruency Relationships Between Cues and Displays in the Target Localization Task

	Response Display	
Cue	Egocentric	Exocentric
Egocentric	Congruent	Incongruent
Exocentric	Incongruent	Congruent
Neutral	Control	Control

and mark them by placing a cursor on top and pressing the joystick button. They were encouraged to use any visual or auditory information they recalled from the original scenario.

Each participant completed six experimental scenarios in two sessions (three scenarios per session), conducted on separate days. Experimental scenarios were followed by workload assessment (using NASA TLX) and the target recall task. The order of conditions was counterbalanced, and participants were randomly assigned to the different orders.

Experimental Design

The experiment used a 2 × 3 within-subject design with map (north up or aircraft up) and auditory cue (egocentric, exocentric, or neutral) serving as independent variables for all tasks. For the target localization task, response display (egocentric or exocentric) also served as an independent variable. The dependent variables differed across tasks: search time for target search, proportion of error and response time (RT) for target localization, and proportion of error for target recall. Performance was evaluated and interpreted in terms of congruency between auditory cues and visual displays across tasks. Table 1 illustrates the congruency relationships between cues and displays for the target localization task.

RESULTS

Target Search Task

Mean search times were computed for each participant in each condition and submitted to a 2 × 3 within-subject analysis of variance (ANOVA) with auditory cue (egocentric, exocentric or neutral) and map (north up or aircraft up) as independent variables. Scheffé's test was used to conduct post hoc comparisons on significant effects for all analyses.

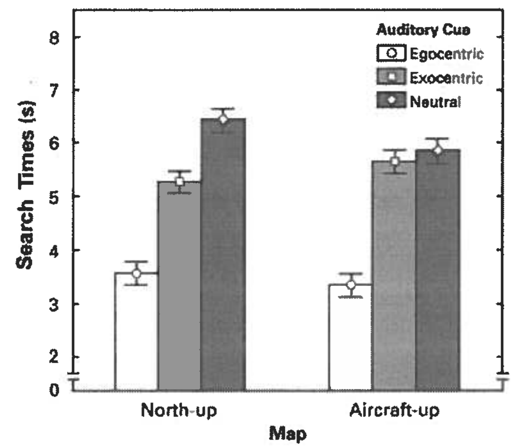

Figure 3. The effect of auditory cue and map on search times. Error bars indicate within-subject 95% confidence intervals (Jarmasz & Hollands, in press) in all graphs.

There was a main effect of auditory cue, $F(2, 46) = 57.75$, $MSE = 162.7$, $p < .0001$. Search was faster with egocentric ($M = 3.45$ s) than with either exocentric ($M = 5.46$ s) or neutral cues ($M = 6.15$; Scheffé's test, $p < .05$ in both cases). In addition, as shown in Figure 3, there was an interaction between map and auditory cue, $F(2, 46) = 3.49$, $MSE = 77.7$, $p < .05$. Exocentric cues produced shorter search times than neutral cues with the north-up map ($p < .05$) but not with the aircraft-up map, for which there was no significant difference between exocentric and egocentric conditions ($p > .05$).

Target Localization Task

Responses were scored as correct or incorrect, and the proportion of error trials was computed for each participant and display condition and submitted to a 2 × 3 × 2 within-subject ANOVA with map (north up or aircraft up), auditory cue (egocentric, exocentric, or neutral), and response display (egocentric or exocentric) serving as independent variables.

There was a main effect for auditory cue, $F(2, 46) = 160.96$, $MSE = 0.03$, $p < .0001$. Errors occurred less often with egocentric ($M = .18$) and exocentric ($M = .23$) auditory cues than with neutral cues ($M = .62$, $p < .05$).

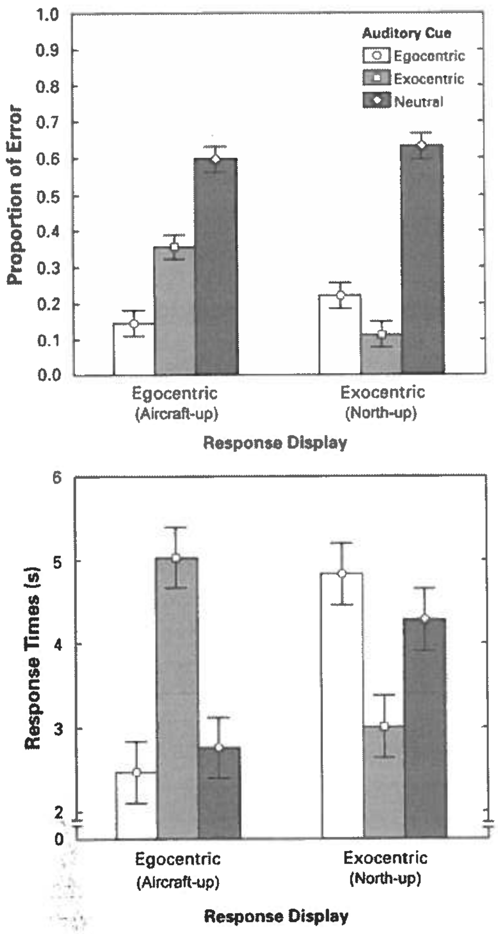

Figure 4. The effect of auditory cue and response display (egocentric = aircraft up, and exocentric = north up) on target localization accuracy and response times.

As shown in Figure 4 (top), there was an interaction between auditory cue and response display, $F(2, 46) = 32.93$, $MSE = 0.02$, $p < .001$. The congruency effect was observed: Egocentric auditory cues produced fewer errors than exocentric cues with egocentric (aircraft-up) response displays, and the opposite pattern was observed for exocentric (north-up) displays ($p < .05$ in both cases).

The interaction also showed that errors occurred less often with north-up response displays than with aircraft-up displays for exocentric auditory cues ($p < .05$), but there was no effect of response display for egocentric or neutral cues ($p > .05$ in both cases). Finally, when auditory

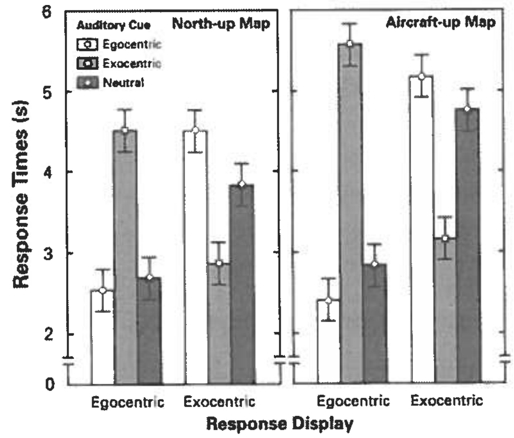

Figure 5. The effect of auditory cue, response display, and map on target localization response times.

cues were egocentric and the visual response display was exocentric (north up), participants made fewer errors than when auditory cues were exocentric and the visual response display was egocentric (aircraft up) ($p < .05$).

Mean RTs for correct trials were computed for each participant in each condition and submitted to a 2 × 3 × 2 within-subject ANOVA with map, auditory cue, and response display serving as independent variables. The analysis showed an interaction between auditory cue and response display, $F(2, 42) = 59.94$, $MSE = 199.4$, $p < .0001$, indicating a congruency effect similar to the error results. As Figure 4 (bottom) shows, egocentric auditory cues produced shorter RTs than did exocentric cues with aircraft-up (egocentric) response displays, but the opposite pattern was observed for north-up (exocentric) displays ($p < .05$ in both cases). However, the interaction also indicated that RTs were shorter with neutral cues than with exocentric cues when egocentric (aircraft-up) response displays were used ($p < .05$). There was no significant difference between neutral cues and egocentric cues with exocentric (north-up) response displays ($p > .05$).

The RT analysis also showed a significant three-way interaction, $F(2, 42) = 4.26$, $MSE = 102.1$, $p < .05$. As Figure 5 shows, the congruency effect that was a component of the two-way interaction was more pronounced in the aircraft-up map condition. That is, the differences between incongruent and congruent conditions were larger in the aircraft-up than the north-up map condition.

Target Recall Task

The number of targets correctly located within 15° to the left or right of the line of sight of the actual target location was computed for each participant and display condition and submitted to a within-subject 2 × 3 ANOVA with map (north up or aircraft up) and auditory cue (egocentric, exocentric, or neutral) serving as independent variables. Target recall did not vary as a function of auditory cue or map, and there was no interaction ($p = 0.11$, $p = 0.62$, $p = 0.98$, respectively). In addition, the overall recall levels were also very low ($M = 3.31$; of 32 targets in total). The same analysis was conducted for a 20° radius, and similar results were obtained.

Subjective Workload

Overall workload scores from the NASA TLX were computed for each participant for each condition and submitted to a 2 × 3 within-subject ANOVA with map (north up or aircraft up) and auditory cue (egocentric, exocentric, or neutral) serving as independent variables. There was a significant main effect of auditory cue, $F(2, 46) = 6.18$, $MSE = 68.40$, $p < .005$. Egocentric cues ($M = 43.20$) produced lower workload scores than did exocentric cues ($M = 49.10$), $p < .05$, but neither differed significantly from the workload scores for neutral cues ($M = 45.50$), $p > .05$ in both cases. There was no main effect for map and no interaction ($p > .05$ in both cases).

DISCUSSION

The purpose of the study was to investigate how RF congruency between auditory cues and visual displays affected performance on spatial tasks. Two types of spatial auditory cues were used in the experiment along with four visual displays, each having egocentric or exocentric properties. Performance on three spatial tasks—target search, localization, and recall—was evaluated relative to a neutral control condition. The cues were congruent with some displays and incongruent with others in terms of the RF used to represent target location.

Results from the target search task showed that targets were found more quickly when the auditory cue was egocentric than when it was exocentric. Workload scores were also lower with egocentric than with exocentric auditory cues. This is consistent with previous studies showing that similar tasks were performed better with more egocentric 3-D perspective displays (Lamb & Hollands, 2005; Olmos et al., 2000; Wickens et al., 1996; Wickens & Prevett, 1995). Given that participants used an egocentric sensor view while in flight and while conducting the search, the reduced search time could be said to demonstrate a congruency effect.This is similar to the findings of Bronkhorst et al. (1996), which showed performance improvements when auditory cues were congruent with the visual RF. When the auditory cue was exocentric, the RFs presumably needed to be mentally aligned to make use of the informational value of the cue, increasing the search time.

Interestingly, an exocentric auditory cue did not improve search times relative to a neutral control when the map was aircraft up (egocentric), even given the cue's informational value relative to the neutral control. However, when the map was north up (exocentric), an exocentric cue was useful, which suggests that the congruency of the exocentric map with the exocentric cue facilitated interpretation of the cue.

In the target localization task, a congruency effect was clearly demonstrated, with greater error and longer RTs when the auditory RFs were incongruent with the visual, relative to congruent, cases; again, this finding is similar to that of Bronkhorst et al. (1996). In incongruent cases, the RFs needed to be aligned, consequently requiring more time and increasing the probability of error. Participants were able to make use of the information provided by the incongruent cues and produced fewer errors than in the neutral control conditions, in contrast to the findings by Barfield et al. (1997), which showed no advantage of auditory cues when they were incongruent with the visual display RF. However, the reduction in error was sometimes obtained at a time cost (when the auditory cue was exocentric and the response display was aircraft up).

In addition, errors on incongruent trials occurred less often when auditory cues were egocentric rather than exocentric. Consider that participants used an egocentric sensor view while in flight, listened to an auditory cue that was either egocentric or exocentric, and then responded with the visual response display. An egocentric-egocentric-exocentric sequence should produce better performance than an egocentric-exocentric-egocentric sequence, because the latter case involved an additional transformation.

The RT differences between incongruent and congruent conditions were larger in the aircraft-up than in the north-up map condition. Having the north-up map reduced the time necessary to interpret incongruent RFs. Perhaps seeing the exocentric north-up map along with the egocentric sensor view facilitated or primed subsequent switches between the RFs of the auditory cues and visual response displays, or it improved situation awareness in general (Lamb & Hollands, 2005; Olmos et al., 2000; Wickens et al., 1996; Wickens & Prevett, 1995).

Finally, the results from the target recall task suggest that although congruent RFs aid immediate performance, there does not appear to be a long-term benefit of more congruent pairings. Perhaps the need to transform with incongruent pairs leads to deeper processing but trades off with any interference among multiple RFs produced during encoding, resulting in no net gain compared with RF congruency. On the other hand, given that this was a delayed memory test conducted subsequent to speeded response tasks, it is also possible that participants did not retain the necessary spatial information to successfully complete this task. The extremely low recall scores (approximately 10% of target locations correctly recalled) are consistent with this hypothesis.

In summary, the results generally highlight the importance of RF congruency between auditory cues and visual displays. The benefit of using auditory cues and visual displays that share a common RF was demonstrated. Congruent auditory cues provided significant accuracy and speed advantages compared with incongruent and neutral cues for target localization.

Moreover, performance advantages were demonstrated with incongruent auditory cues relative to a neutral control condition. This stands in contrast to the results of Barfield et al. (1997), who found that incongruent auditory cues did not provide any advantage over visual only. Thus, we conclude that although it is always best to ensure congruency, there are at least some benefits to providing even incongruent information versus having no spatial information at all.

Implications for Design

The current findings have important implications for display design in complex and dynamic environments that involve RF transformations across displays and tasks, such as SAR, air traffic control, and unmanned aerial vehicle operations. Specifically, although the results confirm that congruent auditory cues should be used whenever possible, when the same cue is to be used across different spatial tasks, egocentric auditory cues should be more effective than exocentric cues.

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