

# Cross-modal Interactions in Time and Space: Auditory Influence on Visual Attention in Hemispatial Neglect

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## Abstract

Recent studies indicate that auditory tone presentation and auditory alerting can temporarily ameliorate visuospatial attention deficits in patients with unilateral neglect [Frassinetti, F., Pavani, F., & Ladavas, E. Acoustical vision of neglected stimuli: Interaction among spatially converging audiovisual inputs in neglect patients. *Journal of Cognitive Neuroscience*, 14, 62–69, 2002; Robertson, I. H., Mattingley, J. B., Rorden, C., & Driver, J. Phasic alerting of neglect patients overcomes their spatial deficit in visual awareness. *Nature*, 395, 169–172, 1998]. The current study investigated proposed mechanisms of cross-modal interaction to determine conditions in which auditory stimulation affects spatial and nonspatially lateralized attention deficits in a patient with hemispatial neglect. In Experiment 1, a target was presented among related distracters (conjunction search) while a tone was presented either bilaterally or in a congruent or incongruent spatial location with respect to the visual target. Whereas the results suggest a benefit of both general alerting and cross-modal spatial integration on visual search efficiency, the most significant improvement occurred when the target and tone were both presented in

contralesional space. In Experiment 2, the effect of auditory alerting on selective attention was examined in a rapid serial visual search procedure with visual targets embedded in a stream of distracters presented at central fixation. When two targets were presented without an alerting tone, the patient missed the second target for up to 1000 msec after the first target appeared (a finding known as the “attentional blink” [AB] and, on average, about 400–500 msec in normals). An alerting tone presented at a fixed temporal location significantly reduced the AB in a tone-duration-dependent manner. Experiment 3 examined the effect of cross-modal space on selective attention in an AB paradigm in which T2 occurred randomly to the left or right of T1 with a spatially congruent or incongruent tone. Discrimination of T2 in contralesional space significantly improved when the tone was presented in the same location, and was impaired when the tone was presented on the ipsilesional side. The findings are discussed as they relate to cross-modal interactions and their influence on spatial and nonspatially lateralized attention deficits in neglect. ■

## INTRODUCTION

In approximately 40–48% of all cases of right-hemisphere brain damage, patients experience a complex array of neurological deficits known as the *neglect syndrome* (Buxbaum et al., 2004; Allegri, 2000). The most prominent feature of neglect is a failure to report, respond, or orient to novel or meaningful stimuli presented to the side of the body opposite a brain lesion (contralesional) in the absence of an elementary sensory or motor deficit (Heilman, Watson, & Valenstein; McFie, Piercy, & Zangwill). Whereas neglect has long been characterized as a deficit in directing attention in space, recent investigations demonstrate that directing attention over time may also be impaired (temporal attention; Baylis, Simon, Baylis, & Rorden, 2002; Duncan et al., 1999; di Pellegrino, Basso, & Frassinetti, 1997, 1998; Husain et al., 1997; Robertson, Manly, et al., 1997; Rorden, Mattingley,

Karnath, & Driver, 1997). Husain, Shapiro, et al. (1997) demonstrated that patients with neglect exhibit a protracted difficulty in detecting the second of two visual targets (T2) embedded in a rapid serial visual presentation (RSVP) of characters after identifying the first target (T1). This effect, called the visual attentional blink (AB), is a robust phenomenon that illustrates the limited capacity of the visual system to process independent stimuli that occur close in time (Raymond, Shapiro, & Arnell, 1992). Compared to neurologically intact, healthy subjects where the AB typically persists for approximately 400 msec, patients with neglect exhibit an AB nearly three times as long. Evidence from studies of patients with neglect (Hillstrom, Husain, Shapiro, & Rorden, 2004) and patients with extinction (Baylis et al., 2002; di Pellegrino et al., 1997, 1998; Rorden et al., 1997) suggests that deficits in temporal attention exist in a spatial gradient with stimuli in contralesional space processed slower than stimuli in ipsilesional space.

Together, spatial and nonspatially lateralized attention deficits associated with neglect contribute to a

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loss of conscious awareness of a significant portion of the environment, a condition that is very disabling and difficult to treat because patients with neglect are often unconcerned with or unaware of their neurological deficits (Hjaltason, Tegner, Tham, Levander, & Ericson, 1996; Robertson, 1993). However, recent studies indicate that cross-modal stimulation (audition cueing vision) can temporarily ameliorate deficits in spatial attention in patients with neglect by improving conscious awareness of contralesional stimuli (Frassinetti, Pavani, & Ladavas, 2002; Robertson, Mattingley, Rorden, & Driver, 1998; Farah, Wong, Monheit, & Morrow, 1989).

Robertson et al. (1998) demonstrated that an auditory alerting tone presented from a speaker located either in front of or to the right of patients with neglect could effectively eliminate the spatial attention bias in a temporal order judgment task. In this study, patients with neglect were simply instructed to make a nonspeeded determination of which horizontal bar, the one to the right or left of fixation, appeared on the computer screen first. On trials in which there was no alerting sound, the horizontal bar to the left of fixation (in neglected space) had to appear on the screen at least 400 msec prior to the bar on the right in order for patients to report that both appeared simultaneously (subjective simultaneity). However, on trials preceded by an alerting tone the bias in spatial attention was eliminated (the study did not, however, distinguish between perceptual vs. postperceptual effects of the tone). The location of the sound source did not appear to alter the effectiveness of the cross-modal manipulation. According to the authors, the improvement may be due to the close relationship between spatial and temporal attention (i.e., common neural substrate that is modulated by arousal).

Although targeting low-level arousal mechanisms irrespective of spatial colocalization across modalities may be effective in ameliorating spatial attention deficits in patients with neglect, another mechanism warrants consideration. A recent study by Frassinetti et al. (2002) demonstrated that the effects of auditory stimulation on visual attention in patients with neglect also occur in a spatially dependent manner. The authors demonstrated improvement in contralesional visual target detection in patients with neglect when an auditory stimulus emanated from the same position in contralesional space, or at close spatial disparity ( $\leq 16^\circ$ ). Improvements were greatest for positions that were more affected by neglect (i.e., the most peripheral positions in the contralesional visual field,  $>40^\circ$  of visual angle from fixation). Unlike Robertson et al.'s (1998) finding, when the sound source was not located close to the spatial position of the visual target there was no cross-modal benefit in detection speed. This finding is consistent with an extensive literature on cross-modal cueing paradigms in neurologically intact, healthy participants (McDonald, Teder-Salejarvi, & Hillyard, 2000;

Schmitt et al., 2000; Dufour, 1999; Driver & Spence, 1998; Spence & Driver, 1997). For example, McDonald et al. (2000) have shown that a sudden nonpredictive tone improves the detectability of a visual stimulus occurring at the same location. Thus, it appears as though shifts of spatial attention in one sensory modality are accompanied by corresponding shifts in other modalities when spatial locations of the two modalities overlap (see evidence from event-related potentials [ERPs]; Eimer, van Velzen, & Driver, 2004; McDonald & Ward, 2000).

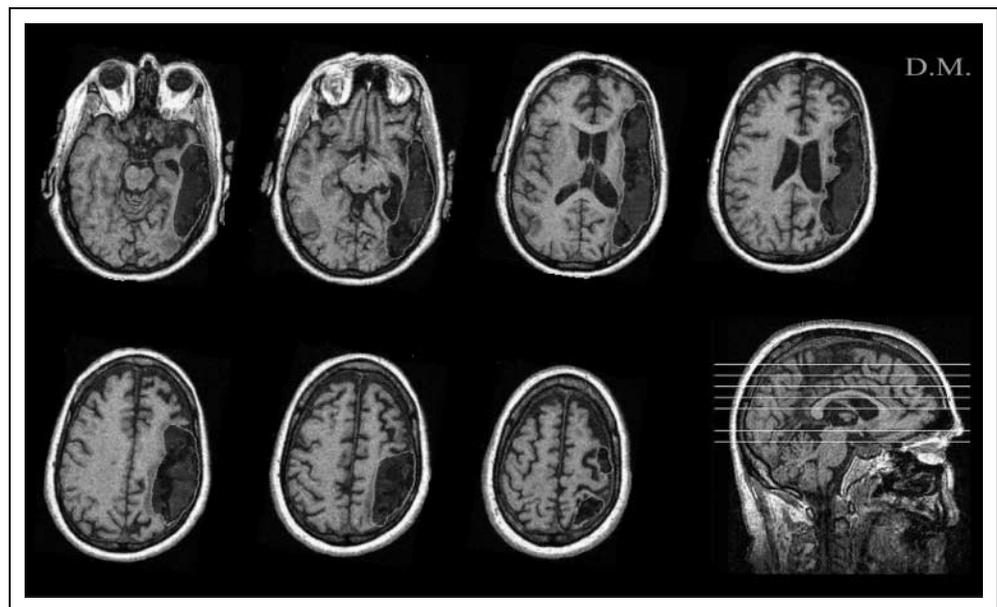
The spatially *dependent* cross-modal effect of sound on visual spatial attention in patients with neglect seems to be a qualitatively different effect than the spatially *independent* effect of auditory alerting. This distinction becomes increasingly relevant when considering strategies for rehabilitation. Should rehabilitation efforts target spatially nonselective deficits in attention or focus on the effects of cross-modal spatial integration? To gain a better understanding of these mechanisms, the current study utilized visual attention tasks and examined the effects of spatially congruent and incongruent auditory stimulation. Considering that patients with neglect most often suffer from deficits in their ability to search and locate stimuli on the neglected side of space, Experiment 1 examined the effect of three tone conditions on an effortful visual conjunction search task: an alerting tone presented bilaterally, a spatially congruent tone, and a spatially incongruent tone. The first experiment provided the opportunity to test the effect of sound on an ecologically valid measure of the spatial deficit exhibited in patients with neglect (Robertson, Eglin, & Knight, 2003; Laeng, Brennen, & Espeseth, 2002; Pavlovskaya, Ring, Groswasser, & Hochstein, 2002; Esterman, McGlinchey-Berroth, & Milberg, 2000; Eglin, Robertson, Knight, & Brugger, 1994; Eglin, Robertson, & Knight, 1989; Treisman & Gelade, 1980). Because differences in the cross-modal effect demonstrated in prior studies may be due to differences in the visual stimulus presentation (stimuli were presented further out from fixation or at a greater visual angle in the Frassinetti et al. [2002] study relative to the Robertson et al. [1998] study, which may have favored a spatially specific effect), targets were located within  $7^\circ$  of visual angle on either side of fixation. Experiment 2 investigated whether an alerting tone, shown to eliminate a bias in spatial attention (Robertson et al., 1998), would produce a similar effect on a temporally demanding measure of selective attention. An alerting tone was randomly presented at a fixed temporal location and at two different durations in a visual AB task where both targets were located at central fixation. Finally, to directly examine the effect of cross-modal space on selective attention, Experiment 3 utilized an AB paradigm where T2 occurred randomly to the left or right of T1 with a spatially congruent or incongruent tone.

## METHODS

### Subject

D.M., a 57-year old man, suffered a large right middle cerebral artery infarct 8 weeks prior to the onset of testing (Figure 1) and demonstrated a severe left neglect. The extent of his stroke included inferior parietal, temporal parietal junction, superior temporal, inferior/middle frontal, and subcortical (lenticular) areas in the right hemisphere, all of which are implicated as key components in a cortical–subcortical network mediating directed attention (Reep et al., 2004; Heilman et al., 2003; Mesulam, 1990). Because the severity of neglect varies across patients and across lesion site (Mort et al., 2003), D.M.'s extensive damage allowed us to test a patient with a relatively severe behavioral and lesion profile. His performance on a standard test battery of neglect (Standard Comprehensive Assessment of Neglect [SCAN]; McGlinchey-Berroth et al., 1996) indicated considerable contralesional omissions on tests of line cancellation, symbol and letter search (average 70% omissions of all contralesional items), an 8-mm average rightward misbisection on a test of line bisection, and evidence of object and space-based neglect on a “living room” copy subtest (e.g., drawing only half of three objects and completely omitting one object on the left). D.M. had full visual fields on neurological exam and intact color vision and hearing; performance on a cognitive screening measure (Mini Mental Status Exam, 29/30) was within normal limits. Data for all the experiments reported was collected in the postacute phase of his injury (within 3 months poststroke), lack of significant variation in performance during this period argues against any possible contribution of spontaneous recovery.

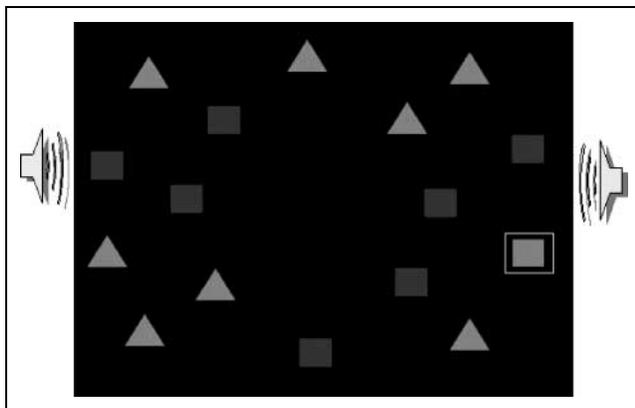
**Figure 1.** Lesion reconstruction of patient D.M. (from T1-weighted magnetic resonance image) Selected axial slices show right-hemisphere lesion extending into inferior parietal, frontal, and temporal lobes.



### Tasks

#### Experiment 1: Conjunction Search

Because neglect is most often defined as a deficit in the ability to attend to and locate relevant information in contralesional space, the conjunction search task, which requires subjects to serially search for a target located among related distracters, provides an ecologically valid measure of the clinically observed deficit in spatial attention. Findings from our laboratory indicate that patients with neglect tested in this paradigm show poor search efficiency for targets in neglected space (Robertson, Eglin, & Knight, 2003; Eglin, Robertson, Knight, et al., 1994; Eglin, Robertson, & Knight, 1989). To examine the influence of alerting versus spatially congruent or incongruent sound on target search efficiency, D.M. was asked to detect a target (e.g., green square) located among distracters (each sharing either the color or shape feature with the target; see Figure 2). Targets randomly appeared in locations to the right or left of fixation ( $2^{\circ}$ – $7^{\circ}$  of disparity) and eye movements were monitored by the experimenter prior to the start of each trial to ensure fixation. Trials were only initiated when D.M. maintained central fixation. The stimuli were presented on a laptop computer screen located 60 cm in front of the patient, and an auditory tone (1000 Hz, 60 dB, 2000 msec) was presented via two external speakers located on either side of the screen ( $10^{\circ}$  to the left and right of fixation, respectively). Because one could argue that the wider visual angle of the targets in the Frassinetti et al. (2002) study allowed a spatial effect to emerge, we presented the conjunction search targets within  $7^{\circ}$  of fixation. We also utilized the same tone parameters reported in the Robertson et al. (1998) study. The spatial overlap between the auditory



**Figure 2.** Schematic representation of the conjunction search display used in Experiment 1 (figure not to scale). The target (green square) is highlighted for illustration. Speaker icons represent the location of the sound sources.

signal and the visual target in the congruent condition was within  $2^{\circ}$ – $4^{\circ}$  of visual angle and incongruent sound-target locations were separated by  $11^{\circ}$ – $16^{\circ}$  of visual angle. In the sound conditions, the tone was presented at the onset of the visual stimulus array to control for cueing effects. Presentation latency of the visual stimulus array was adjusted according to the participant's performance via a psychophysical staircase procedure (Kaernbach, 2001). Presentation time was fit to a 75% accurate target detection threshold. Presentation time began at 2000 msec and was adjusted in increments of  $\Delta T = 6 - [(r + 1) - \text{mod}((r + 1), 2)]/2$  screen frames, where  $r$  = the number of reversals encountered,  $\text{mod}(a, b)$  is the remainder after division of  $a$  by  $b$ , and screen frame duration = 16 msec. Detection thresholds were concurrently estimated separately for left and right targets. Detection thresholds for each condition were based on the last 8 of 10 reversals in the staircase for that block. Using this procedure, estimates of threshold presentation time for target detection could be established in a relatively short period (5–7 min). Sound/target conditions (e.g., congruent, incongruent, bilateral, no sound) with random target location (left, right) were blocked and counterbalanced over four testing sessions. On half of all trials within a block there was no target, and in the remaining trials the visual target occurred equally often in a congruent as an incongruent location relative to the sound source. Thus, the sound location was not predictive of the location of the visual target as they were colocalized on only 25% of the total trials.

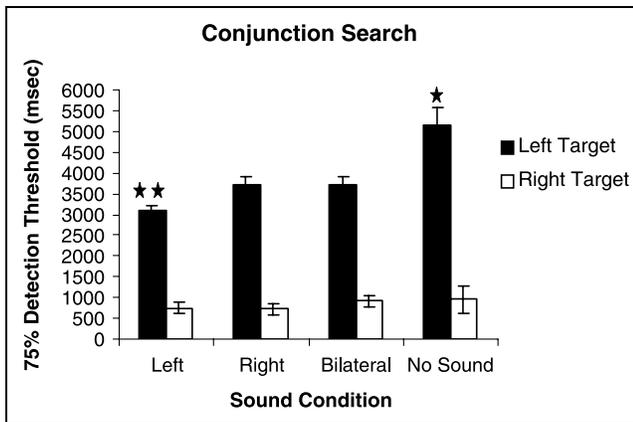
#### *Experiment 2: Central Visual Attentional Blink*

D.M. was tested in a conventional (Shapiro, Raymond, & Arnell, 1994; Raymond et al., 1992) visual AB paradigm consisting of an RSVP of letters (subtending  $2^{\circ}$  of visual angle vertically,  $1^{\circ}$  horizontally) presented in the center

of the screen at fixation with either one (single task) or two (dual task) numbers embedded in the stream. Each character was presented on the screen for 80 msec with a 20-msec interstimulus interval. White letters (distracters) and red numbers (targets) were used to maximize identification, and 14 total items were presented in each stream/trial. Because the stream of visual information occurred at fixation, an area of space where D.M. demonstrated an ability to identify targets on standardized testing, the likelihood of an overlapping deficit due to a bias in spatial attention was reduced. In a separate block of trials, first target (T1) was not attended, and D.M. only had to report the identity of T2 (single task). These trials are important because they demonstrate that he was capable of detecting and correctly identifying T2 when not attending to T1. On both single- and dual-task trials, T2 discrimination was a four alternative forced-choice judgment rather than a presence/absence judgment, preventing D.M. from conservative reporting of target detection when targets were not clearly attended. D.M. verbally reported the identity of the targets; the experimenter (blind to the experimental condition) coded responses via an external numeric keyboard. The alerting tone (1000 Hz, 60 dB for either 300 or 100 msec) was presented on half the trials and emanated from two speakers located on either side of the monitor ( $10^{\circ}$  to the left and right of fixation, respectively). The tone onset occurred at a fixed temporal interval (immediately following the offset of the T1 mask) so as not to provide a temporal cue for the appearance of T2 (the onset of T2 varied randomly between 0 and 700 msec posttone). D.M. was run on four separate days for a total of 40 trials per condition. Figure 3 illustrates a typical dual-task trial.

#### *Experiment 3: Spatially Lateralized Attentional Blink*

Stimuli were presented similarly to the method used in Experiment 2. However, T2 was separated by  $4^{\circ}$  of visual angle from T1 (located at fixation) on the same horizontal plane. T2 could appear randomly to the left or right of fixation, and each character (target or distracter) was presented on the screen for 100 msec with a 25-msec interstimulus interval (longer than Experiment 2 due to the increased difficulty of shifting spatial location; see Hillstrom et al., 2004). White letters (distracters) and red numbers (targets) were used to maximize identification and 14 total items were presented in each stream/trial. As in Experiment 2, in a separate block of trials the first target was not attended, and D.M. only had to report the identity of T2 (single task). He was asked to report both targets during dual-task blocks. The tone (1000 Hz, 60 dB for 100 msec) was presented on half the trials and was presented from one of two speakers located on either side of the monitor ( $10^{\circ}$  to the left and right of fixation, respectively). The spatial overlap between the auditory signal and the visual target



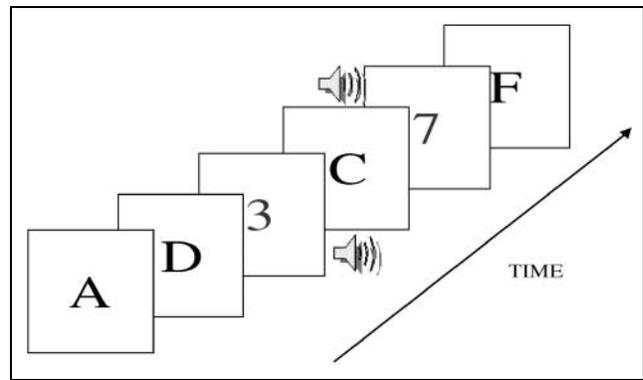
**Figure 3.** Search efficiency (75% detection threshold) as a function of sound condition for targets occurring to the left and right of fixation. A “★” indicates that the mean 75% detection threshold for the no-sound condition was significantly longer than any other condition for left targets. A “★★” indicates that the 75% detection threshold for the left sound condition was significantly shorter than any other condition on the left following analysis of the factors leading to a significant Sound × Target Side interaction.

in the congruent condition was within 4° of visual angle, and incongruent sound-target locations were separated by 16° of visual angle. The tone onset occurred at a fixed temporal interval (immediately following the offset of the T1 mask) so as not to provide a temporal cue for the appearance of T2 (the onset of T2 varied randomly between 0 and 650 msec posttone). D.M. verbally reported the identity of the targets; the experimenter (blind to the experimental condition) coded responses via an external numeric keyboard. Seventy percent of trials contained both T1 and T2, whereas the remaining 30% only contained T1. Forty trials per condition were collected over four testing sessions. In addition, as in Experiment 2, T2 discrimination was a four-alternative forced-choice judgment rather than a presence/absence judgment. Figure 4 illustrates a typical dual-task trial.

## RESULTS

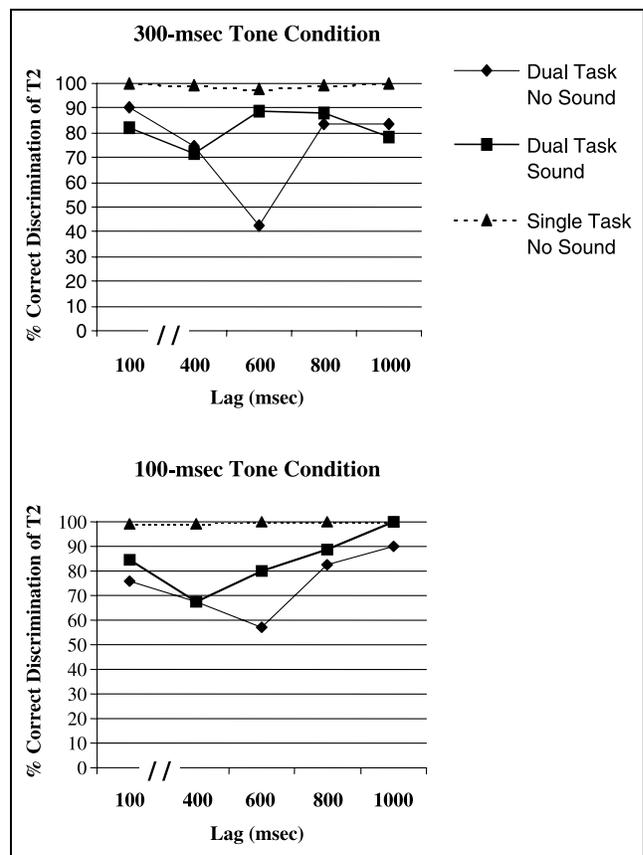
### Experiment 1

The first experiment demonstrated that the same tone could improve visual search efficiency when presented bilaterally and when presented from a congruent spatial location with respect to the visual target compared to no sound. Figure 5 illustrates that, as expected, on no-sound trials D.M. demonstrated slower search efficiency for targets in the neglected side of space compared to the intact side (5140 vs. 980 msec,  $p_s < .01$ ). Because each condition was tested independently of the other conditions and the order of conditions was randomized across sessions, the detection threshold for each trial was treated as an independent event in the statistical analysis. A repeated measures ANOVA on mean detection thresholds with Target Side (left, right) and Sound



**Figure 4.** Schematic representation of the stimuli used in Experiment 2. All stimuli, including target 1 (T1) and target 2 (T2), occurred at fixation. On alerting trials, the sound (300 or 100 msec) was presented at a fixed temporal location (immediately after the offset of the T1 mask).

(left, right, bilateral, and no sound) as factors revealed a significant main effect of Sound,  $F(3,30) = 11.946$ ,  $p < .0001$ , and a significant interaction between Sound and Target Side,  $F(3,30) = 8.101$ ,  $p < .0001$ . Planned com-



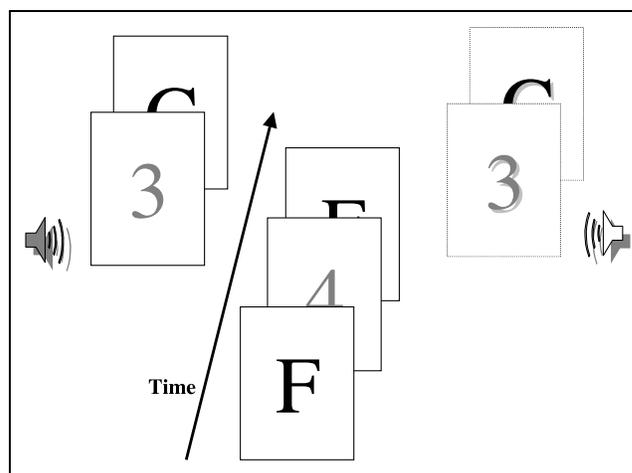
**Figure 5.** Percent correct T2 discrimination as a function of the temporal onset of the second target (T2). On single-task trials, only T2 was reported; on dual-task trials, both targets were reported. Temporal “Lags” represent time of T2 presentation relative to T1 presentation. Tone was presented immediately following the offset of the T1 mask.

parisons found that although a bilaterally presented sound was effective in significantly improving D.M.'s search efficiency for targets in neglected space compared to the no-sound condition, 3718 vs. 5140 msec;  $t(1) = 8.70, p < .01$ , it was not as effective as a spatially congruent sound, 2664 vs. 3718 msec;  $t(1) = 9.35, p < .01$ . Thus, the left sound condition was found to be the most effective condition following analysis of the factors leading to the significant Sound  $\times$  Target Side interaction. The significant effect of spatial congruency over and above other tone conditions in this patient argues for a robust effect of cross-modal spatial integration on attention in contralesional space. Whereas no significant effects were found for targets on the right across conditions, a trend toward a spatial congruency benefit was evident as has been shown in normals (Dufour, 1999). It is also possible that given the effect size of sound on left targets compared to right targets, any difference between sound conditions on the right were obscured by a floor effect. Finally, given the features of sound used in this experiment, it is unlikely that any preattentive auditory perceptual grouping influenced performance (Vroomen & de Gelder, 2000).

Because the results of Experiment 1 suggest that both mechanisms (arousal and cross-modal spatial integration) contributed to greater search efficiency, Experiments 2 and 3 attempted to examine the unique contribution of each mechanism on a temporally demanding selective attention task with and without a lateralized spatial component. The fine temporal resolution of the AB task allowed us to explicitly examine the effect of sound on temporal processing speed. Because the reported AB in patients with neglect lasts nearly 1400 msec, significantly shorter than the duration of the tone used in Experiment 1, Experiment 2 examined the effect of two shorter tones in an AB task where all stimuli were presented at central fixation.

## Experiment 2

In this AB task, D.M. had to identify either one (single task) or two (dual task) targets embedded in a stream of distracters (see Figure 3). Figure 6 shows D.M.'s discrimination accuracy for reporting T2 under various conditions. In the dual task, T2 accuracy was calculated only for trials in which T1 was correctly reported. Accurate discrimination of T2 in the single-task condition indicates that poor T2 discrimination in the dual-task condition was not due to a basic inability to perceive the second target. In the dual-task/no-sound condition, D.M. exhibited a protracted AB (up to 1000 msec, detailed below). Because many studies utilizing the AB examine performance in participants younger than D.M., the same task (no-sound condition) was administered to six neurologically intact, healthy, age-matched controls (four women and two men ages 54–60 years, mean age 59 years) to determine if perhaps the pro-



**Figure 6.** Schematic representation of stimuli used in Experiment 3. The first target (T1) was always presented at central fixation. The second target (T2) occurred on the same horizontal plane, randomly to the right or left of T1. Shaded components of the figure depict a trial in which T2 appears to the left of T1. Tone was presented at a fixed temporal location (immediately following the offset of the T1 mask) and could emanate from a congruent or incongruent spatial location with respect to T2 (shaded speaker in figure represents a congruent trial).

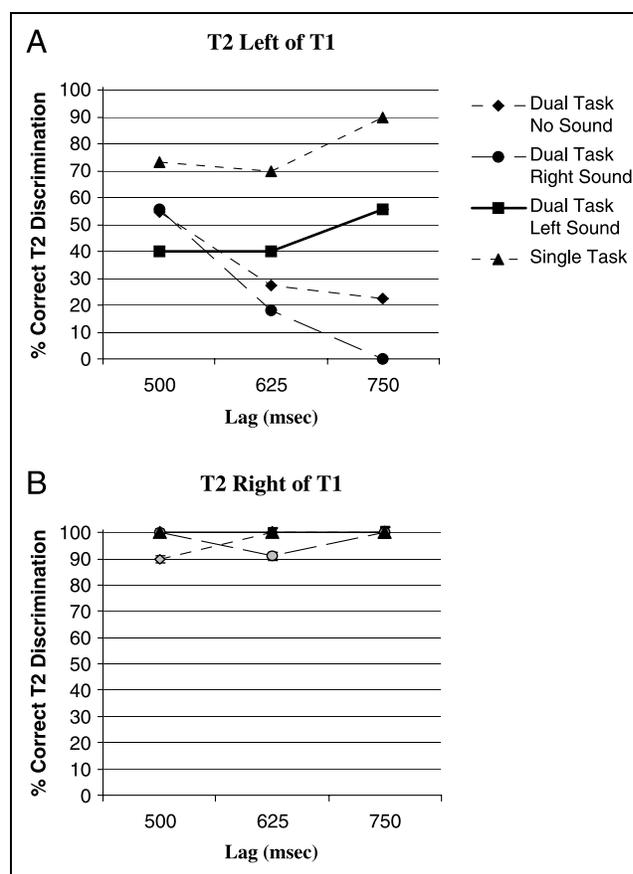
tracted AB was simply a product of D.M.'s age. Performance on the AB task in controls revealed a shorter and shallower AB than D.M. (mean T2 discrimination accuracy in the dual task for controls: 100-msec lag = 88, 400-msec lag = 74, 600-msec lag = 86, 800-msec lag = 85, and 1000-msec lag = 96). For controls, a repeated measures ANOVA on mean percent T2 accuracy with Task (Dual, Single) and Stimulus Onset Asynchrony (SOA; five lags) as factors found a significant main effect of Task,  $F(1,40) = 52.826, p < .0001$ ; Lag,  $F(4,40) = 4.221, p < .006$ , and a significant Task  $\times$  Lag interaction,  $F(4,40) = 3.916, p < .009$ . Simple effects tests found that performance on the dual-task condition was significantly worse than performance on the single task for the 400- and 600-msec lags only ( $ps < .01$ ). Thus, it is unlikely that D.M.'s protracted AB is simply a product of his age.

On trials in which a 300-msec alerting tone was present, D.M. demonstrated a significant improvement in his ability to discriminate the second visual target in the dual-task condition. A repeated measures ANOVA on arcsine transforms of T2 accuracy with Task (Dual, Single), SOA (five lags), and Sound (No Sound, Sound) as factors found the following: significant main effects of SOA,  $F(4,48) = 8.424, p < .001$ , and Sound,  $F(1,12) = 4.743, p < .05$ ; significant interactions between SOA and Task,  $F(4,48) = 8.036, p < .001$ ; SOA and Sound,  $F(4,48) = 12.053, p < .001$ ; Sound and Task,  $F(1,12) = 5.00, p < .045$ ; and a significant three-way interaction between Task, Sound, and Lag,  $F(4,48) = 11.583, p < .001$ . Simple effects tests found that in the dual-task condition, when T2 appeared at time lag 3, sound

significantly improved D.M.'s discrimination accuracy compared to the no-sound condition,  $F(1,6) = 29.313$ ,  $p < .02$ . Similarly, in the 100-msec tone duration condition, a repeated measures ANOVA on arcsine transforms of T2 accuracy with Task (Dual, Single), SOA (five lags), and Sound (No Sound, Sound) as factors found the following: significant main effects of SOA,  $F(4,48) = 20.175$ ,  $p < .0001$ , and Sound,  $F(1,12) = 18.452$ ,  $p < .001$ ; significant interactions between SOA and Task,  $F(4,48) = 19.164$ ,  $p < .001$ , SOA and Sound,  $F(4,48) = 2.716$ ,  $p < .04$ , and Sound and Task,  $F(1,12) = 19.231$ ,  $p < .01$ . Simple effects tests found that in the dual-task condition, when T2 appeared at time lag 3 and 5, sound significantly improved D.M.'s T2 discrimination accuracy compared to the no-sound condition,  $F(1,6) = 37.884$ ,  $p < .001$ ;  $F(1,6) = 6.00$ ,  $p < .05$ . To compare the effect of tone duration, a one-way ANOVA comparing difference scores between dual-task/no-sound and dual-task/sound conditions at the 600-msec lag for the 300- versus the 100-msec tone condition (at the most profound level of the blink and attenuation of the blink) revealed a significantly smaller benefit on T2 discrimination accuracy with a shorter tone,  $F(1,6) = 8.09$ ,  $p < .029$ , at this lag. Thus, the results of Experiment 2 are consistent with a prior study (Robertson et al., 1998) in demonstrating that an alerting tone can have beneficial effects on temporal attention. The results of the current study also show that this effect can occur in a temporally demanding selective attention task in which relevant targets must be attended and irrelevant distracters ignored. It is also important to note that this improvement in discrimination accuracy occurred in relatively intact attentional space (central fixation) in the absence of a competing ipsilesional stimulus (Robertson et al., 1998), and appeared to be tone duration dependent.

### Experiment 3

To examine the effect of spatially lateralized tones on temporal, selective attention, we again utilized the AB paradigm. In this experiment we separated targets (T1 and T2) in space and utilized a tone duration that was shown to produce less of an alerting effect. When only T2 was reported (single task), T2 accuracy was lower overall when T2 appeared to the left compared to when T2 appeared to the right (78% for left vs. 97% for right targets; Figure 7). Although SOA had no systematic influence on T2 accuracy for right targets, D.M. demonstrated improved T2 discrimination at each successive lag. A significant difference between right and left target discrimination accuracy was also evident when both targets were attended (dual task). On trials in which T2 appeared to the right of T1 the number of targets reported did not reliably influence T2 response accuracy at any SOA ( $ps > .05$ ). Thus, there was no



**Figure 7.** Percent correct T2 discrimination as a function of the temporal onset of the second target (T2) occurring (A) to the left of T1 and (B) to the right of T1. On dual-task trials, both targets were reported. In the single-task condition, only T2 was reported. Temporal “lags” represent time of T2 presentation relative to T1 presentation. Tone was presented immediately following the offset of the T1 mask. In (B), icons for “Dual Task No Sound” and “Dual Task Right Sound” conditions have been shaded gray to aid identification.

evidence of an AB when T2 was on the right (consistent with Hillstrom et al., 2004, see Discussion section). When T2 was on the left, however, T2 accuracy was significantly impaired. A repeated measures ANOVA run on arcsine transforms of T2 accuracy, looking at the effect of number of targets reported or Task (Single Report, Dual Report), SOA (three time lags), and Sound (No Sound, Congruent Sound, Incongruent Sound) found the following: significant main effects of Sound,  $F(2,18) = 28.092$ ,  $p < .001$ , significant interactions between Sound and Task,  $F(2,18) = 34.120$ ,  $p < .001$ , SOA and Sound,  $F(4,36) = 32.440$ ,  $p < .001$ , and a significant three-way interaction between Sound, Task, and Lag,  $F(4,36) = 51.677$ ,  $p < .001$ . Planned comparisons revealed that congruent sound in the dual task was significantly better (40%) than either incongruent (18%) or no sound (27%) at the 625-msec lag ( $p < .0001$  and  $p < .003$ , respectively) and also at the 750-msec lag ( $ps < .0001$ ) Incongruent sound in the dual task

at the 750-msec lag (0%) was significantly worse than both congruent (56%) and no-sound (22%) conditions ( $p < .0001$ ).

## DISCUSSION

Consistent with prior studies (Frassinetti et al., 2002; Robertson et al., 1998), the results of the current study indicate that an auditory event can ameliorate spatial and nonspatially lateralized attention deficits in a patient with neglect. The results suggest that the effect of cross-modal spatial integration may add to the effect of alerting in visual search with a prolonged tone. Whereas a prolonged sound (2000 msec) produced significant facilitation of contralesional target detection irrespective of location compared to no sound in Experiment 1, a spatially congruent tone produced the most significant improvement. The results of Experiments 2 and 3 indicate that the effects of alerting and cross-modal spatial integration may be somewhat dissociable in selective attention. A short tone (100 msec), shown to produce less of an effect on temporal processing than a longer tone (300 msec) when both targets appeared at fixation, produced both facilitation and inhibition of contralesional target discrimination in a location-dependent manner (i.e., tone presented on the same side of space produced better discrimination accuracy, whereas a tone presented on the opposite side impaired discrimination in Experiment 3). Overall, the results indicate a consistent and sustained beneficial effect of audiovisual spatial integration on visual attention in a patient with hemispatial neglect.

### Visual Search

The results of Experiment 1 are consistent with prior studies demonstrating the benefit of audiovisual spatial integration on detection in patients with neglect (Frassinetti et al., 2002; Farah et al., 1989). However, as the search task in the current study utilized a psychophysical staircase (Kaernbach, 2001), the patient was not required to initiate a speeded response. Thus, motor or response deficits commonly observed in neglect were controlled.

Several studies conducted in neurologically intact, healthy individuals provide possible interpretations for the current results (McDonald et al., 2000; Schmitt et al., 2000; Vroomen & de Gelder, 2000; Dufour, 1999; Driver & Spence, 1998; Spence & Driver, 1997). First, the effect of sound on visual search has been shown to be spatially specific for detection of targets consisting of conjoined features located among related feature distracters (conjunction search; Dufour, 1999). The necessity of spatial attention to bind features in conjunction search tasks has been demonstrated in numerous stud-

ies in both patients and normals (Robertson, Eglin, & Knight, 2003; Laeng et al., 2002; Pavlovskaya et al., 2002; Esterman et al., 2000; Eglin et al., 1994; Eglin, Robertson, & Knight, 1989; Treisman & Gelade, 1980). The role of spatial attention in conjoining features has also been demonstrated in tasks that do not require explicit processing of distracters (Briand & Klein, 1987). Thus, it is possible that cross-modal stimulation in the current study provided a more stable or precise representation of space than that tied to a single sense, such as retinotopic location in vision or craniotopic location in audition. A number of studies in normals suggest that shifts of spatial attention in one sensory modality are accompanied by corresponding shifts in other modalities when spatial locations of the two modalities overlap (McDonald et al., 2000; Schmitt et al., 2000; Driver & Spence, 1998; Spence & Driver, 1997).

The notion of an involuntary supramodal spatial attentional mechanism is supported by recent studies examining ERPs (Eimer et al., 2004; McDonald & Ward, 2000) and neuroimaging (Macaluso, Frith, & Driver, 2002a, 2002b, 2002c). McDonald and Ward (2000) found that orienting spatial attention to an irrelevant sound modulates the ERP to a subsequent visual target over modality-specific, extrastriate visual cortex. Eimer et al. (2004) have also shown that early attentional modulation of visual and auditory ERPs were found for stimuli at relevant versus irrelevant locations within the same hemifield and that the modulation occurred in both the task-relevant and irrelevant modality (Eimer et al., 2004). Similarly, Macaluso et al. (2002a, 2002b, 2002c) demonstrated that the blood oxygen level dependent (BOLD) response to visual stimuli increased in primary visual areas with the presence of a spatially congruent, task-irrelevant tactile stimulation.

Cross-modal modulations of primary sensory and extrastriate areas in the intact brain likely represent reentrant feedback from higher intermodal areas such as the superior temporal gyrus, intraparietal sulcus, and inferior frontal lobe (Bushara et al., 2003; Saito, Okada, Morita, Yonekura, & Sadato, 2003; Macaluso et al., 2002a, 2002b, 2002c; Lewis, Beauchamp, & DeYoe, 2000). However, patients with neglect, like D.M., often have damage to these cortical structures and suffer from significant lapses in awareness of stimuli across modalities. Thus, it is likely that an alternative mechanism is facilitating cross-modal synergy in the damaged brain. Significant work in animals indicates that a subset of neurons in the superior colliculus respond to stimuli in more than one modality and that these neurons are arranged topographically (e.g., unimodal visual and auditory neurons overlap with spatially corresponding receptive fields) (Stein, Stanford, Wallace, Vaughan, & Jiang, 2004; Stein & Meredith, 1993). These neurons show supra-additive responses to multimodal stimulation occurring at the same location compared with responses

to unimodal stimulation. The output of these neurons is particularly robust with subthreshold or weak multimodal signals (e.g., weak visual and weak auditory signals as often evident in neglect) occurring in the same spatial location (inverse effectiveness rule; Stein & Meredith, 1993).

Whereas evidence from both behavioral and physiological studies accentuate the critical role of space in cross-modal interactions, the results of Experiment 1 and those from another study (Robertson et al., 1998) indicate that auditory alerting, irrespective of spatial location, can also affect visual attention in neglected space. Search efficiency for contralesional targets in Experiment 1 improved (albeit significantly less than in the spatially congruent condition) when a tone was presented either bilaterally or ipsilesional to the target location compared to no sound. Investigations of visual processing in healthy individuals have led to the proposal that visual stimuli normally compete for selection by a limited-capacity system (Desimone & Duncan, 1995). Studies examining patients with extinction (Baylis et al., 2002; di Pellegrino et al., 1997, 1998; Rorden et al., 1997) and neglect (Hillstrom et al., 2004; Husain et al., 1997) suggest that the capacity or speed of visual processing may be reduced on the contralesional compared to the ipsilesional side of space. For example, when two objects are presented simultaneously, the ipsilesional item may win in the competition for attentional selection due to “prior entry.” Although it has been demonstrated that alerting can eliminate prior entry irrespective of sound source location in patients with neglect (Robertson et al., 1998), this mechanism cannot entirely account for the results of Experiment 1 or the results from a prior study (Frassinetti et al., 2002). Because the differences in the effect of sound on visual attention in patients with neglect may be attributable to differences in task parameters (detection vs. search) or paradigms (temporal order judgment [TOJ] vs. conjunction search vs. detection speed), Experiments 2 and 3 allowed us to make a more direct comparison between spatially mediated and nonspatially mediated mechanisms of cross-modal influence on visual attention.

### Selective Attention

The results of Experiment 2 indicate that alerting can beneficially affect selective attention (attending relevant targets while ignoring irrelevant distracters) in a patient with neglect. This effect may also be tone duration dependent, as a longer (300 msec) tone produced significantly greater T2 discrimination accuracy than a shorter tone (100 msec). Whereas a similar effect of sound on temporal attention has been demonstrated for a stimulus occurring in contralesional space relative to a competing ipsilesional stimulus (Robertson et al., 1998), the current effect was shown in relatively

intact attentional space in the absence of an ipsilesional competitor.

The beneficial effect of alerting on nonspatially lateralized processing deficits in patients with neglect is significant, but important questions remain regarding the underlying mechanism(s). According to Robertson et al. (1998), auditory alerting activates “intact thalamic–mesencephalic projections” that shift attention leftward. Engaging the reticular activating system (or intact thalamic–mesencephalic projections) via alerting theoretically lowers the threshold for activation of both hemispheres, reestablishing a balance of activation and eliminating the bias in spatial attention (Kinsbourne, 1977). Alerting may also activate spared processing mechanisms in areas of the frontal–parietal network that are involved in both spatial and nonspatially lateralized attention (Husain & Rorden, 2003; Wojciulik & Kanwisher, 1999; Coull & Frith, 1998). However, damage to this circuitry is often indicated in the production of neglect (D.M. suffered extensive damage to both frontal and parietal areas).

Alternatively, it has been suggested that the AB is not a failure of selective attention, but rather a failure to properly update working memory with a reportable representation of T2 (Vogel, Luck, & Shapiro, 1998). As has been shown for spatial working memory (Husain et al., 2001; Wojciulik, Husain, Clarke, & Driver, 2001), perhaps patients with neglect also have trouble with nonspatial working memory that may account for their protracted AB (but see Pisella et al., 2004). If so, perhaps the tone in the current study facilitated this updating process enabling D.M. to more accurately report T2. Anecdotally, on dual-task alerting trials in which D.M. could not identify T2, he frequently reported that he had a “sense” of the identity of T2, a sort of “tip of the tongue” phenomenon. This sense was not reported on no-sound dual-task trials in which T2 was missed. Also, because patients with neglect also demonstrate impaired sustained attention (Robertson et al., 1997), it may be possible that the tone simply facilitated continuous engagement with the task. However, the short duration of a single AB trial (<3 sec) makes this an unlikely explanation. It may also be argued that because the tone was presented at a fixed temporal interval, it could have disrupted processing of T1, freeing up resources for T2 processing. If this were the case it would be expected that D.M. would have demonstrated better discrimination of T2 when present at lag 1 or lag 2, temporal locations closer to the tone. Furthermore, the tone was presented immediately after the offset of the T1 mask, thus not affecting the perceptual termination of T1.

Recent data from Olivers and Nieuwenhuis (2005) and Arend, Johnston, and Shapiro (2005) provide a novel and compelling interpretation of AB attenuation. Olivers and Nieuwenhuis demonstrated that noncontingent music was able to nearly fully attenuate a visual AB in

normals. The authors contend that music creates an “attentional state” that reduces the dual-target interference. Similarly, when Arend et al. introduced apparent motion around the visual targets in an AB task they also demonstrated a significant reduction in the blink (motion appearing to move away from the target produced greater AB attenuation than motion toward the target). The authors conclude that the background task attenuated an unnecessary overallocation of attention to the first target. Although this effect may have contributed to the results in Experiment 2, it is an unlikely explanation for the results of Experiment 3. Specifically, if the attenuating mechanism requires attention to be “drawn away” from the AB stimuli (apparent motion away from stimuli produced the greatest effect in the Arend et al. study), it would be expected that a sound from an incongruent location would have produced the greatest attenuation of the AB. The results of Experiment 3 indicate that spatial incongruency actually produced a greater blink.

### Selective Attention Across Space

In the absence of cross-modal manipulation, the results of Experiment 3 are consistent with a similar, recent case study by Hillstrom et al. (2004). Both studies demonstrated that when T2 is presented contralateral to T1, both patients with neglect demonstrated a protracted AB. However, no processing delay was reported when T2 appeared ipsilateral to T1 in either study. Better than anticipated performance on the right is consistent with the results of previous investigations demonstrating hyperattention toward stimuli on the right in patients with neglect (Smania et al., 1998; Gainotti, D’Erme, & Bartolomeo, 1991; Ladavas, Petronio, & Umiltà, 1990; De Renzi, Gentilini, Faglioni, & Barbieri, 1989). However, when sound was introduced in the current experiment, the results demonstrated a clear effect of space on audiovisual facilitation of contralateral T2 discrimination (cost for tone/target incongruency and benefit for tone/target congruency compared to no sound). This suggests that cross-modal spatial integration is a vital component when selectively attending relevant information in contralateral space in this patient. The lack of a significant effect of alerting (i.e., incongruent sound did not enhance T2 discrimination) may be attributable to the sound parameters. The utilization of a shorter tone (100 msec) may have diminished the arousing/alerting effect of the sound. Thus, arousal-mediated reduction in hemispheric competition and/or increased processing speed for targets in contralateral space cannot entirely account for the effect. In addition, the tone was most effective at SOAs 350- to 400-msec posttone offset, approximately the same time in which the AB was most profound and the tone most efficient in the central AB task. Findings from patients with right-hemisphere lesions indicate that cue-related disengagement from ipsilateral

stimuli is larger at shorter cue-target SOAs, and decreases as SOA increases (Losier & Klein, 2001). Thus, cross-modal facilitation or cost in the current study was not entirely due to a reduction or amplification of a disengagement deficit. Rather, an alternative interpretation consistent with recent physiological data (Eimer et al., 2004; McDonald & Ward, 2000) and data from animal studies (Stein & Meredith, 1993) would indicate that involuntary shifts of covert attention in the visual modality occurred with the presentation of the tone.

### Implications for Rehabilitation

The integrated visual/auditory system offers a unique opportunity to improve the functional capacity of patients with visual neglect. The spatial integration of visual and auditory information can potentially enable patients to detect bimodal stimuli for which unimodal components are below the threshold of conscious awareness. According to the inverse effectiveness rule (Stein & Meredith, 1993), the improvement should be greater for the visual positions that are more affected by the spatial impairment, that is, the most peripheral positions in contralateral space. Although this is supported by a prior study (Frassinetti et al., 2002) in which the most significant cross-modal effect occurred for contralateral targets located at 40° of visual angle from central fixation, the results of the current study demonstrated that this effect is also evident at locations much closer to fixation (within 7° of visual angle; see also Farah et al., 1989). These findings have important implications for rehabilitation of patients with hemispatial neglect. Focusing efforts on increasing cross-modal attention in a spatially specific manner may prove beneficial beyond simply boosting arousal.

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### REFERENCES

- Allegri, R. F. (2000). Attention and neglect: Neurological basis, assessment and disorders. *Reviews in Neurology*, 30, 491–494.
- Arend, I., Johnston, S., & Shapiro, K. (2005). *Illusory motion attenuates the attentional blink*. Poster presented at the Visual Sciences Society 2005 annual meeting.
- Baylis, G. C., Simon, S. L., Baylis, L. L., & Rorden, C. (2002). Visual extinction with double simultaneous stimulation: What is simultaneous? *Neuropsychologia*, 40, 1027–1034.
- Briand, K. A., & Klein, R. M. (1987). Is Posner’s “beam” the same as Treisman’s “glue”? On the relation between visual orienting and feature integration theory. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 228–241.
- Bushara, K. O., Hanakawa, T., Immisch, I., Toma, K., Kansaku, K., & Hallett, M. (2003). Neural correlates of cross-modal binding. *Nature Neuroscience*, 6, 190–195.

- Buxbaum, L. J., Ferraro, M. K., Veramonti, T., Farne, A., Whyte, J., Ladavas, E., Frassinetti, F., & Coslett, H. B. (2004). Hemispatial neglect: Subtypes, neuroanatomy, and disability. *Neurology*, *62*, 749–756.
- Coull, J. T., & Frith, C. D. (1998). Differential activation of right superior parietal cortex and intraparietal sulcus by spatial and nonspatial attention. *Neuroimage*, *8*, 176–187.
- De Renzi, E., Gentilini, M., Faglioni, P., & Barbieri, C. (1989). Attentional shift towards the rightmost stimuli in patients with left visual neglect. *Cortex*, *25*, 231–237.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Reviews in Neuroscience*, *18*, 193–222.
- di Pellegrino, G., Basso, G., & Frassinetti, F. (1997). Spatial extinction on double asynchronous stimulation. *Neuropsychologia*, *35*, 1215–1223.
- di Pellegrino, G., Basso, G., & Frassinetti, F. (1998). Visual extinction as a spatio-temporal disorder of selective attention. *NeuroReport*, *9*, 835–839.
- Driver, J., & Spence, C. (1998). Cross-modal links in spatial attention. *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences*, *353*, 1319–1331.
- Dufour, A. (1999). Importance of attentional mechanisms in audiovisual links. *Experimental Brain Research*, *126*, 215–222.
- Duncan, J., Bundesen, C., Olson, A., Humphreys, G., Chavda, S., & Shibuya, H. (1999). Systematic analysis of deficits in visual attention. *Journal of Experimental Psychology: General*, *128*, 450–478.
- Eglin, M., Robertson, L. C., & Knight, R. T. (1989). Visual search performance in the neglect syndrome. *Journal of Cognitive Neuroscience*, *4*, 372–381.
- Eglin, M., Robertson, L. C., Knight, R. T., & Brugger, P. (1994). Search deficits in neglect patients are dependent on size of the visual scene. *Neuropsychology*, *4*, 451–463.
- Eimer, M., van Velzen, J., & Driver, J. (2004). ERP evidence for cross-modal audiovisual Effects of endogenous spatial attention within hemifields. *Journal of Cognitive Neuroscience*, *16*, 272–288.
- Esterman, M., McGlinchey-Berroth, R., & Milberg, W. P. (2000). Parallel and serial search in hemispatial neglect: Evidence for preserved preattentive but impaired attentive processing. *Neuropsychology*, *14*, 599–611.
- Farah, M. J., Wong, A. B., Monheit, M. A., & Morrow, L. A. (1989). Parietal lobe mechanisms of spatial attention: Modality-specific or supramodal? *Neuropsychologia*, *27*, 461–470.
- Frassinetti, F., Pavani, F., & Ladavas, E. (2002). Acoustical vision of neglected stimuli: Interaction among spatially converging audiovisual inputs in neglect patients. *Journal of Cognitive Neuroscience*, *14*, 62–69.
- Gainotti, G., D'Erme, P., & Bartolomeo, P. (1991). Early orientation of attention toward the half space ipsilateral to the lesion in patients with unilateral brain damage. *Journal of Neurology, Neurosurgery, and Psychiatry*, *54*, 1082–1089.
- Heilman, K. M., Watson, R. T., & Valenstein, E. (2003). Neglect and related disorders. In K. M. Heilman & E. Valenstein (Eds.), *Clinical neuropsychology* (4th ed., pp. 296–346). London: Oxford University Press.
- Hillstrom, A. P., Husain, M., Shapiro, K. L., & Rorden, C. (2004). Spatiotemporal dynamics of Attention in visual neglect: A case study. *Cortex*, *40*, 433–440.
- Hjaltason, H., Tegner, R., Tham, K., Levander, M., & Ericson, K. (1996). Sustained attention and awareness of disability in chronic neglect. *Neuropsychologia*, *34*, 1229–1233.
- Husain, M., Mannan, S., Hodgson, T., Wojculik, E., Driver, J., & Kennard, C. (2001). Impaired spatial working memory across saccades contributes to abnormal search in parietal neglect. *Brain*, *124*, 941–952.
- Husain, M., & Rorden, C. (2003). Non-spatially lateralized mechanisms in hemispatial neglect. *Nature Reviews Neuroscience*, *4*, 26–36.
- Husain, M., Shapiro, K., Martin, J., & Kennard, C. (1997). Abnormal temporal dynamics of visual attention in spatial neglect patients. *Nature*, *385*, 154–156.
- Kaernbach, C. (2001). Adaptive threshold estimation with unforced-choice tasks. *Perception & Psychophysics*, *63*, 1377–1388.
- Kinsbourne, M. (1977). Hemi-neglect and hemisphere rivalry. *Advances in Neurology*, *18*, 41–49.
- Ladavas, E., Petronio, A., & Umiltà, C. (1990). The deployment of visual attention in the intact field of hemineglect patients. *Cortex*, *26*, 307–317.
- Laeng, B., Brennen, T., & Espeseth, T. (2002). Fast responses to neglected targets in visual search reflect pre-attentive processes: An exploration of response times in visual neglect. *Neuropsychologia*, *40*, 1622–1636.
- Lewis, J. W., Beauchamp, M. S., & DeYoe, E. A. (2000). A comparison of visual and auditory motion processing in human cerebral cortex. *Cerebral Cortex*, *10*, 873–888.
- Losier, B. J., & Klein, R. M. (2001). A review of the evidence for a disengage deficit following parietal lobe damage. *Neuroscience and Biobehavioral Reviews*, *25*, 1–13.
- Macaluso, E., Frith, C. D., & Driver, J. (2002a). Directing attention to locations and to sensory modalities: Multiple levels of selective processing revealed with PET. *Cerebral Cortex*, *12*, 357–368.
- Macaluso, E., Frith, C. D., & Driver, J. (2002b). Supramodal effects of covert spatial orienting triggered by visual or tactile events. *Journal of Cognitive Neuroscience*, *14*, 389–401.
- Macaluso, E., Frith, C. D., & Driver, J. (2002c). Crossmodal spatial influences of touch on extrastriate visual areas take current gaze direction into account. *Neuron*, *34*, 647–658.
- Malhotra, P., Mannan, S., Driver, J., & Husain, M. (2004). Impaired spatial working memory: One component of the visual neglect syndrome? *Cortex*, *40*, 667–676.
- McDonald, J. J., Teder-Salejarvi, W. A., & Hillyard, S. A. (2000). Involuntary orienting to sound improves visual perception. *Nature*, *407*, 906–908.
- McDonald, J. J., & Ward, L. M. (2000). Involuntary listening aids seeing: Evidence from human electrophysiology. *Psychological Science*, *11*, 167–171.
- McFie, J., Piercy, M. F., & Zangwill, O. L. (1950). Visual-spatial agnosia associated with lesions of the right cerebral hemisphere. *Brain*, *73*, 167–190.
- McGlinchey-Berroth, R., Bullis, D. P., Milberg, W. P., Verfaellie, M., Alexander, M., & D'Esposito, M. (1996). Assessment of neglect reveals dissociable behavioral but not neuroanatomical subtypes. *Journal of International Neuropsychological Society*, *2*, 441–451.
- Mesulam, M. M. (1990). Large-scale neurocognitive networks and distributed processing for attention, language, and memory. *Annals of Neurology*, *28*, 595–613.
- Mort, D. J., Malhotra, P., Mannan, S. K., Rorden, C., Pambakian, A., Kennard, C., & Husain, M. (2003). The anatomy of visual neglect. *Brain*, *126*, 1986–1997.
- Olivers, C. N., & Nieuwenhuis, S. (2005). The beneficial effect of concurrent task-irrelevant mental activity on temporal attention. *Psychological Science*, *16*, 265–269.
- Pavlovskaya, M., Ring, H., Groswasser, Z., & Hochstein, S. (2002). Searching with unilateral neglect. *Journal of Cognitive Neuroscience*, *14*, 745–756.

- Pisella, L., & Mattingley, J. B. (2004). The contribution of spatial remapping impairments to unilateral visual neglect. *Neuroscience and Biobehavioral Reviews*, *28*, 181–200.
- Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 849–860.
- Reep, R. L., Corwin, J. V., Cheatwood, J. L., Van Vleet, T. M., Heilman, K. M., & Watson, R. T. (2004). A rodent model for investigating the neurobiology of contralateral neglect. *Cognitive and Behavioral Neurology*, *17*, 191–194.
- Robertson, I. H. (1993). Cognitive rehabilitation in neurologic disease. *Current Opinion in Neurology*, *6*, 756–760.
- Robertson, I. H., Manly, T., Beschin, N., Daini, R., Haeske-Dewick, H., Homberg, V., Jehkonen, M., Pizzamiglio, G., Shiel, A., & Weber, E. (1997). Auditory sustained attention is a marker of unilateral spatial neglect. *Neuropsychologia*, *35*, 1527–1532.
- Robertson, I. H., Mattingley, J. B., Rorden, C., & Driver, J. (1998). Phasic alerting of neglect patients overcomes their spatial deficit in visual awareness. *Nature*, *395*, 169–172.
- Robertson, L. C., Eglin, M., & Knight, R. T. (2003). Grouping influences in unilateral visual neglect. *Journal of Clinical and Experimental Neuropsychology*, *25*, 297–307.
- Rorden, C., Mattingley, J. B., Karnath, H., & Driver, J. (1997). Visual extinction and prior entry: Impaired perception of temporal order with intact motion perception after unilateral parietal damage. *Neuropsychologia*, *35*, 421–433.
- Saito, D. N., Okada, T., Morita, Y., Yonekura, Y., & Sadato, N. (2003). Tactile–visual cross-modal shape matching: A functional MRI study. *Cognitive Brain Research*, *17*, 14–25.
- Schmitt, M., Postma, A., & De Haan, E. (2000). Interactions between exogenous auditory and visual spatial attention. *Quarterly Journal of Experimental Psychology*, *53*, 105–130.
- Shapiro, K. L., Raymond, J. E., & Arnell, K. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 357–371.
- Smania, N., Martini, M. C., Gambina, G., Tomelleri, A., Palamara, A., Natale, E., & Marzi, C. A. (1998). The spatial distribution of visual attention in hemineglect and extinction patients. *Brain*, *121*, 1759–1770.
- Spence, C., & Driver, J. (1997). Audiovisual links in exogenous covert spatial orienting. *Perception and Psychophysics*, *59*, 1–22.
- Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. Cambridge: MIT Press.
- Stein, B. E., Stanford, T. R., Wallace, M.T., Vaughan, W. J., & Jiang, W. (2004). Crossmodal spatial interactions in subcortical and cortical circuits. In C. Spence & J. Driver (Eds.), *Crossmodal space and crossmodal attention* (pp. 25–50). Oxford University Press.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97–136.
- Vogel, E. K., Luck, S. J., & Shapiro, K. J. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1656–1674.
- Vroomen J., & de Gelder, B. (2000). Sound enhances visual perception: Cross-modal effects of auditory organization on vision. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 1583–1590.
- Wojciulik, E., Husain, M., Clarke, K., & Driver, J. (2001). Spatial working memory deficit in unilateral neglect. *Neuropsychologia*, *39*, 390–396.
- Wojciulik, E., & Kanwisher, N. (1999). The generality of parietal involvement in visual attention. *Neuron*, *23*, 747–764.