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## Spatial deployment of attention within and across hemifields in an auditory task

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**Abstract** Research on visual attention has demonstrated that covert attention can be focused on particular locations within one hemifield, but that a specific “meridian” cost may also be found for shifting attention between hemifields. These issues have received less consideration for audition, even though reliable behavioral measures for the effects of spatial attention on hearing are now available. We examined the spatial distribution of covert attention in an auditory task following spatially non-predictive peripheral auditory cues (which should induce exogenous attention shifts), or following symbolic central cues that predicted the likely location for the auditory target (to induce endogenous attention shifts). In both cases, we found that attention can be focused not only on one hemifield versus another, but also within one hemifield in an auditory task. However, there was no unequivocal evidence for a meridian effect in audition.

**Keywords** Auditory · Spatial attention · Exogenous · Endogenous · Meridian effect

### Introduction

A number of models have been developed to describe how covert attention may be focused on different regions of space. Each of these models makes different predictions, which have been tested in vision. However, the spatial distribution of attention has not been examined as thoroughly for other sensory modalities. In this article we investigate the distribution of covert spatial attention in an *auditory* task, to see whether the underlying mech-

anisms follow similar principles to those proposed for vision.

Three models for the spatial distribution of visual attention can be broadly distinguished. The simplest is a “hemifield-wide” model, according to which attention can only be directed to one visual field versus the other, perhaps by activation of the contralateral hemisphere (Kinsbourne 1993). Such a model was proposed for vision by Hughes and Zimba (1985, 1987), who presented some supporting evidence from visual detection studies with spatial cues in an otherwise empty scene. However, numerous studies have since shown that spatial cueing effects can arise *within* one visual hemifield (e.g. Downing and Pinker 1985; Shulman et al. 1985; Klein and McCormick 1989; LaBerge and Brown 1989; Rizzolatti and Camarda 1987; Egly and Homa 1991; Henderson 1991). Moreover, on theoretical grounds, hemifield-wide selection seems too crude a mechanism for visual attention. Vision can build a spatially precise model of the external environment, and relevant objects will often compete for selection with other objects, even within the same hemifield. Nevertheless, a hemifield-wide model might still be appropriate for the auditory domain, where spatial resolution is much poorer. Moreover, the few spatial cueing studies of attention for audition (e.g. see Spence and Driver 1994, 1996, 1997; Scharf 1998) have typically compared performance for only two lateral target positions, one on each side, and hence their results could be accommodated by a hemifield-wide model.

Findings that covert attention can be focused within a hemifield to affect *visual* performance (Downing and Pinker 1985; Shulman et al. 1985, 1986; LaBerge and Brown 1989) led to a second class of model, on which attention can be distributed in a graded fashion, with maximal processing at the focus of attention, which gradually falls off with increasing distance from this focus. Such a “gradient” model could be realized in terms of changing neuronal excitation (and/or attenuation) within spatiotopic maps of the external input. In simplest form, gradient models do not imply that shifts of atten-

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tion between hemifields (e.g. when a target appears on the left after a cue on the right) should induce any particular extra cost, other than that dictated by cue-target distance. The gradient hypothesis need not be tied to vision, although most previous work motivated by it has focused exclusively upon that modality. In principle, spatiotopic maps of auditory information could also be utilized by an attentional system, to provide a basis for the graded distribution of attention to affect auditory performance.

A third account of spatial attention is Rizzolatti and colleagues' "premotor" model, which suggests that covert attentional shifts in the standard cueing paradigms (Posner 1980) are driven by planned but as yet unexecuted motor programs (Rizzolatti et al. 1994). Rizzolatti et al. (1987) noted that this model might explain the "meridian" effect they found in a cueing study of covert visual attention – a specific performance penalty when cue and visual target appeared in opposite hemifields, and thus in different directions from central fixation. Their study had four possible target locations, two in each hemifield. At the start of each trial, a central cue informed the subject that the visual target was most likely to appear at a specific target location (thus, the cue was spatially informative, and should induce endogenous covert orienting). On a minority of trials, the cue was "invalid"; a visual target appeared at one of the other three locations, which each occurred equiprobably. Subjects made a speeded detection response to the target, regardless of location. Rizzolatti et al. (1987) found fastest reaction times at the cued location. The critical new result was that responses were particularly slow to invalid targets in the uncued *hemifield*, compared with invalid targets in the cued hemifield which were just as far from the cue. This "meridian effect" was interpreted by Rizzolatti et al. in terms of premotor theory. Assuming that changes in the *direction* of a motor plan (which may require the selection of different muscles) are harder than changes merely in *amplitude*, then the greater cost when shifting attention to a different hemifield (and thus in a different direction from central fixation) might conceivably be explained in terms of internal motor plans.

Rizzolatti et al.'s (1987) visual results seem at odds with predictions from the hemifield-wide account, and with (simple) gradient models. The former would expect a cost for crossing between hemifields, but without the specific benefit for the cued location *within* the cued hemifield that was observed. A simple gradient model might expect no specific cost for crossing a hemifield, provided cue-target distance is equated for the invalid trials that are compared. However, Downing and Pinker (1985) suggested that attentional gradients around the current focus of attention may be steeper near the fovea for vision, since most cortical visual maps exhibit substantial "cortical magnification". This could in principle lead to the appearance of an attentional penalty for shifting attention between hemifields in vision in some experiments, which is in fact due merely to steeper gradients near the midline for the visual modality. However, Rizzolatti et al. (1987) presented a row of possible target

locations six degrees from fixation, presumably thus minimizing any influence of cortical magnification near the fovea. The most straightforward prediction from gradient models is simply a particular advantage for the cued location, plus some advantage for any positions close to it.

Since Rizzolatti et al.'s (1987) pioneering design seems able to distinguish between these three models for the distribution of spatial attention in visual tasks, we adapted it here to test which model holds best for the case of the effects of spatial attention upon *auditory* performance. Rizzolatti et al. (1994) suggested that the premotor theory describes spatial attention in general, independent of specific sensory modalities, which suggests that a meridian effect should be found for auditory targets as well as for visual, if the origin of this effect is indeed as the premotor account supposes. Some evidence already exists that might be interpreted as suggesting a link between motor programming and auditory processing. Hikosaka and Wurtz (1989) found that neurons responding to auditory stimulation, in the monkey's substantia nigra, fired more vigorously to a sound in their receptive field if an eye movement was subsequently made towards that sound. Rorden and Driver (1999) demonstrated in humans that upcoming saccades can influence auditory performance, with better auditory judgements in the direction of a planned saccade. This suggests that premotor theory might extend to the auditory as well as visual domain. However, to date all the evidence for the meridian effect, commonly taken to support premotor theory, has come from purely *visual* studies.

In summary, while the three models for the distribution of covert spatial attention (hemifield-wide, gradient and premotor-meridian) have been tested in vision, each remains largely untested for audition. Though the hemifield-wide model has been discounted for vision, it may be a possibility for the less spatially precise modality of audition. Moreover, most previous auditory cueing studies (e.g. Spence and Driver 1994, 1996) used only two lateral positions, one in each hemifield, so no meridian effect could be assessed. A test similar to that conducted by Rizzolatti et al. (1987), but applied to an auditory task instead of a visual task, should distinguish between the three models for spatial attention in audition.

In conducting such a test, it is important to distinguish between exogenous covert attention (reflexive shifts following peripheral cues) and endogenous covert attention (voluntary strategic shifts following informative cues), since the principles by which these two forms of covert orienting operate may differ for auditory tasks (see Spence and Driver 1994), just as has been previously claimed on the basis of visual studies (Jonides 1976; Jonides 1981; Yantis and Jonides 1984; Briand and Klein 1987; Lambert et al. 1987; Müller and Rabbitt 1989; Warner et al. 1990; Yantis and Johnson 1990; Rafal et al. 1991; Remington et al. 1992; Rizzolatti et al. 1994).

Each of our experiments investigated the effect of either endogenous or exogenous spatial attention on au-

ditory performance, seeking to determine the spatial distribution of covert attention following either central or peripheral cues. The first experiment used informative central cues in an attempt to elicit purely endogenous orienting. This study closely followed the design of Rizzolatti et al.'s (1987) study, which had initially demonstrated meridian effects in a visual task. The second experiment used spatially non-predictive peripheral cues, in an attempt to shift just exogenous spatial attention.

## Experiment 1

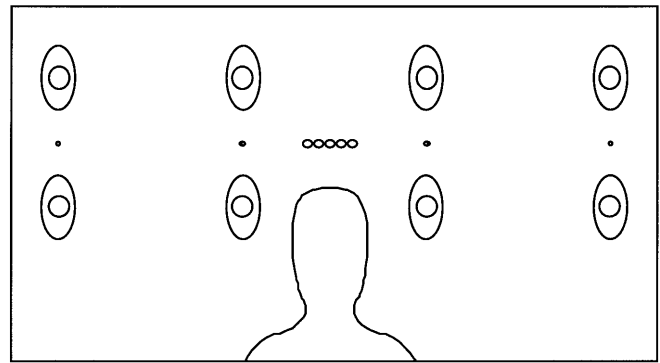
Past studies reporting meridian and/or hemifield-wide attentional effects in vision all used spatially predictive cues (Hughes and Zimba 1985, 1987; Reuter-Lorenz and Fendrich 1992; Umiltá et al. 1991). Accordingly, experiment 1 used informative central cues that predicted the likely location of the auditory target, with a design modeled on Rizzolatti et al.'s (1987) visual study. Since recent research has suggested that eye position can influence performance in auditory tasks (e.g. Rorden and Driver 1999, their experiment 2), fixation was monitored throughout, to ensure that any cueing effects were the result of covert shifts of attention, not overt shifts of eye position.

The task was adapted from Spence and Driver's (1994, 1996) previous work on spatial attention in the auditory domain, which found reliable effects of both endogenous and exogenous covert spatial attention upon auditory judgements. Unlike the present study, their previous experiments only considered one lateral position within each hemifield, so that the three models for the distribution of covert attention could not be distinguished. Nevertheless, their basic task provides a reliable measure for the impact of covert spatial attention upon audition. In this task, subjects make an elevation judgement (up versus down) for auditory targets, regardless of which side they appear on. Covert attention is directed to one side or the other prior to the target, by a cue. Targets on the cued side are typically judged faster than those on the uncued side (e.g. Spence and Driver 1994, 1996). Since the direction of lateral cueing is entirely orthogonal to the up/down dimension that is judged, such a cueing effect cannot be attributed to response-priming or criterion shifts. In the present study, this basic up/down task was adapted so that the auditory targets could appear at four different lateral positions (outer left, inner left, inner right, outer right), with attention being cued to one of these lateral positions, analogous to Rizzolatti et al.'s (1987) visual study (see Fig. 1).

## Materials and methods

### Subjects

Twenty-seven participants were recruited; six were rejected because their accuracy was less than 70% in the auditory task. Of the remaining subjects, nine were male, 12 female, and all were right handed. Age ranged from 19 to 29 years with a median age of 20.



**Fig. 1** The experimental set-up, as seen from behind and above the subject's head. Eight speakers (depicted as *ovals* surrounding *small circles*) were arranged in four columns. Small lights (shown as *dots*) marked the eccentricity of the speaker columns, at an intermediate height. A small fixation light was located directly in front of the subject, directly flanked by four lights which were used for symbolically cueing the likely side and eccentricity for the target sound in experiment 1, as described in the text

The experiment required about 55 min, and the volunteers were each paid £3.60 for their participation.

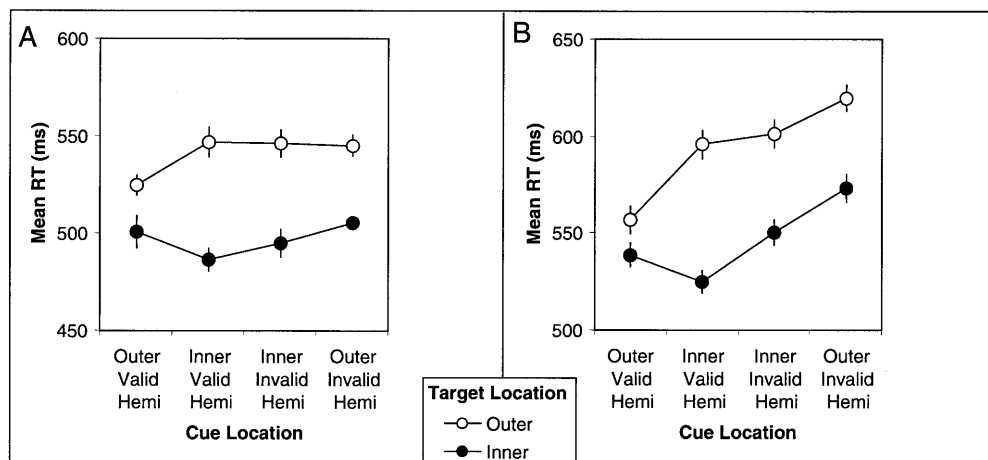
### Apparatus and materials

The experiment was conducted in a darkened anechoic chamber (178×122×91 cm). Subjects sat at a table, facing forward, with head movement restrained by a chin and nose rest. Seat height was adjusted so that the ears were always at an intermediate height between the upper and lower speakers.

A yellow central fixation LED was placed directly in front of the subject. Target sounds were presented from any one of eight oval loudspeakers (each 5×3 inch RS 245-304), each mounted 57 cm away from the subject (all measurements are from the center of the loudspeakers). The speakers were mounted in pairs (one 15° above and one 15° below the subject's eye level, for a vertical separation of 30°), at 17° and 51° laterally to both the left and right of the subject, to form four "columns" of two speakers each (see Fig. 1). Each speaker column was marked visually by a permanently illuminated LED at eye level (i.e. midway between the two speakers within each column), which was red or green for 17° versus 51°, respectively. The likely lateral position of the target sound on each trial was cued via four LEDs situated very close to the central fixation light; red LEDs at 1° on the right versus left cued the right or left inner column of speakers respectively, while green LEDs at 2° to the right versus left cued the outer speakers on their respective sides. Note that while these symbolic cues were presented in the visual modality, they should induce a purely auditory expectancy, as they predicted the likely location only for the upcoming *auditory* target. Indeed, all target events were presented within audition.

Each target's sound was created by three 20-ms bursts from a white noise generator at a volume of 83 dB (A), with successive bursts separated by 20 ms gaps, to yield a 100-ms pulsed target. These complex target sounds are relatively easy to localize in elevation as well as azimuth for most listeners (Spence and Driver 1994). Subjects indicated whether the sound was above or below them, regardless of target side, by pressing one of two micro-switches mounted immediately in front of them, with the thumb versus index finger of their preferred hand. Subjects were asked to look straight ahead at the fixation light throughout the experiment, with this instruction repeated before each block of trials. Position of the left eye was monitored with an ASL EyeTrac 210 infrared eye monitor interfaced via a 12-bit analog-digital-converter to the computer. Trials where the eye deviated more than 3° to the left or

**Fig. 2** Mean reaction times (RT, in ms) for experiment 1 (left graph) and experiment 2 (right graph), as a function of cue location. Experiment 1 used central informative cues, experiment 2 used peripheral non-predictive cues, in an otherwise similar task. Data are shown for inner versus outer target locations (lower line with filled symbols, versus upper line with open symbols)



**Table 1** Mean reaction times (RT, in ms) and errors (%) for experiment 1

Target position		Valid hemifield cue		Invalid hemifield cue	
		Outer cue	Inner cue	Inner cue	Outer cue
Inside target	RT (ms)	539	524	550	573
	Errors (%)	9.3	8.3	9.2	10.2
Outside target	RT (ms)	557	596	601	620
	Errors (%)	9.9	9.1	9.7	6.6

right of fixation were excluded from analysis (recall that the nearest target column was 17° eccentric). The algorithm for detecting saccades did tend to false alarm to blinks, but this was considered acceptable as it allowed the saccade criterion to remain conservative.

The experiment was controlled by a Viglen 3/33 (IBM 386 compatible) computer. Manual reaction time to make the up/down discrimination for each auditory target was measured in milliseconds from the target onset, using an 82C54 interval-timer chip. Input/output from eye monitor, and for the stimuli and responses, were handled by Blue Chip Technologies parts DCM-16 and DOP-24.

#### Procedure

The sequence of events for each trial was as follows. Each trial was initiated by the fixation light. The symbolic visual cue was then presented (400 ms later) at one of four LEDs near central fixation, for 100 ms. After a randomly-chosen cue-target stimulus onset asynchrony (SOA) of anywhere between 600 and 800 ms the pulsed white-noise target was presented (lasting for 100 ms). The trial continued until the subject had pressed a response key indicating whether the target came from one of the upper or one of the lower positions, or until 2000 ms had elapsed without a response. During the first (practice) block only, incorrect responses were followed by the central light blinking for 300 ms, to help the subject learn the auditory elevation discrimination task. In all blocks, the central light went off to signal the end of each trial, which was then followed by a 500 ms inter-trial interval.

Subjects completed 12 blocks of eighty trials each, including the first (practice) block. During each block, each of the four possible central cues was used to produce 14 valid trials (seven upper targets, seven lower targets) and two invalid trials (one upper and one lower target) for each of the three remaining columns, in an otherwise random sequence. The central cue thus had a validity of 70% for predicting the auditory target's lateral location (at outer-left, inner-left, inner-right or outer-right). Note that the cue never predicted whether the auditory target would be from above or below, and thus did not predict the required response.

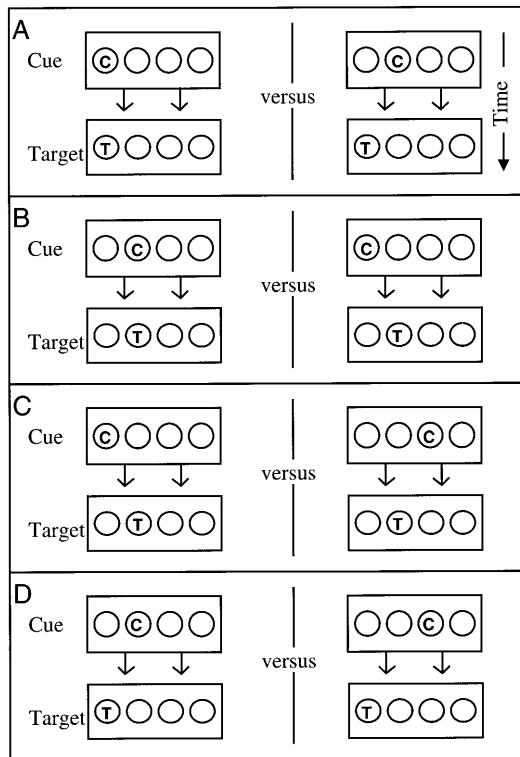
#### Results

The data were collapsed across height (top and bottom targets) and side (left and right targets), as Spence and Driver (1994) reported no significant difference between these factors using a very similar method and apparatus in the same laboratory. Trials in which the eye signal indicated a possible shift away from fixation were excluded from analysis (12.5%, though the majority of these trials were due to blinks rather than overt eye movements). Trials with reaction times outside of 150–1500 ms were also excluded (less than 1%).

Mean results for the critical conditions are shown graphically in the left panel of Fig. 2. The graph shows two separate lines for the inner (lower line) and outer (upper line) auditory target positions. The abscissa denotes the four possible cued locations. The mean reaction time and error data are given numerically in Table 1.

A two-way ANOVA was conducted, with target location (two levels: inner 17°, outer 51°) and cue location (four levels: 51° or 17° in the same hemifield as target, and 17° or 51° in the opposite hemifield) as within-subject variables. Inner targets were responded to significantly more quickly than Outer targets [ $F(1,20)=45.4$ ,  $P<0.001$ ; 547 versus 594 ms]. This better localization of sounds at positions nearer the midline is a standard finding in auditory psychophysics, and relates to the physics of sounds in relation to forward-facing ears, and heads that cast auditory "shadows" (e.g. see Moore 1985).

Cue location was also found to be a significant factor [ $F(3,60)=22.7$ ,  $P<0.001$ ]. Critically, a Target by Cue interaction was also found [ $F(3,60)=4.5$ ,  $P<0.006$ ], sug-



**Fig. 3** Schematic depiction of the conditions considered in the critical pairwise comparisons. The tests compared the effect of different cued locations (“C” indicates the cued position) on response time for a specific target location (“T”). For example, comparison **A** (at top) examined whether a validly-cued outer target was judged better than the same target when preceded by an invalid cue indicating the *inner* location within the target’s hemifield. Note that the cue was central, symbolic and predictive in experiment 1, but peripheral and nonpredictive in experiment 2. The first two comparisons (**A**, **B**) explore whether attention can be focused within a hemifield in the auditory task. The second two comparisons (**C**, **D**) test for any “meridian” effect of crossing hemifields

gesting the presence of some cueing effects that were spatially specific. Examining this interaction with pairwise comparisons is needed to assess the predictions from the three models for spatial attention that were considered above.

A critical aspect of the methodology here is to compare different cued locations for the same target, rather than different targets for the same cue, since the inner and outer targets differed in eccentricity and the RTs for them are not directly comparable. There are four relevant planned pairwise comparisons, two for each type of target (inner versus outer); all were examined using paired *t*-tests. The comparisons are illustrated schematically in Fig. 3 (but note that in this experiment the cues were central, indicating the cued likely target location only in a symbolic manner). The first two comparisons directly test Hughes and Zimba’s (1985, 1987) hemifield-wide hypothesis, which predicts no difference between a condition where the target location was correctly cued, versus with an invalid cue in the correct hemifield. By con-

trast, both the premotor and gradient models predict a specific benefit for the valid targets. For outer-target trials (see Fig. 3A for a schematic of the comparison), this benefit was clearly found, with faster performance [ $t(20)=4.2$ ,  $P<0.001$ , which remains significant at  $P<0.01$  after Bonferroni correction] for valid targets (mean of 557 ms) than for invalid targets with a cue indicating the same hemifield (mean=596 ms). This provides strong evidence against the hemifield-wide hypothesis, for the case of purely endogenous spatial attention effects upon audition. The finding is compatible with the predictions of both the premotor and gradient models.

The second pairwise comparison (see Fig. 3B for a schematic) examines the case of an inner target that was validly cued, versus invalidly cued by the outer location in the correct hemifield. This comparison did not reach significance [ $t(20)=1.4$ ,  $P<0.15$ , means of 524 ms versus 539 ms], although the small trend was for a valid advantage. We discuss this pattern later.

We next consider whether there is any cost for crossing between hemifields, consistent with a meridian effect. The third planned comparison (see Fig. 3C for schematic) examined an inner target cued either by an outer cue in the correct hemifield ( $34^\circ$  away from the target) or by an inner cue in the incorrect hemifield (also  $34^\circ$  away from the target). This comparison proved non-significant [ $t(20)=5.6$ ,  $P<0.19$ ], apparently counter to the hemifield-wide model and to the premotor prediction of a meridian effect, but consistent with a gradient model on which auditory attention can be focused to a lateral area subtending less than  $34^\circ$ .

The fourth comparison (see Fig. 3D for schematic) examined an outer target following an inner cue in either the correct hemifield ( $34^\circ$  away from the target) or the incorrect hemifield ( $68^\circ$  away from the target). Unlike the previous comparison, this does not equate cue-target distance across the different types of trial, and so a significant difference could be compatible with several models. However, finding no difference would be incompatible with the hemifield-wide model, and also the premotor prediction of a meridian effect. Such an outcome could be reconciled with an attentional gradient with a fairly tight focus, such that there is virtually no change in the gradient (which would presumably have bottomed out) between the two invalid locations, since both are quite far ( $34^\circ$  or more) from the cued locus. Analysis showed no difference between these conditions [ $t(20)=0.5$ ,  $P<0.63$ ]; this aspect of the results therefore provides no support for the hemifield-wide model, nor for the premotor meridian prediction, and hence favors a gradient account over those alternatives.

Error rate data were also examined by a two-way ANOVA with the same factors used in the reaction time analysis. There was no main effect of target location [ $F(1,20)=0.4$ ,  $P<0.51$ ] or cue position [ $F(3,60)=0.5$ ,  $P<0.71$ ], and no interaction between target position and cue position [ $F(3,60)=1.6$ ,  $P<0.19$ ]. The planned *t*-test pairwise comparisons conducted above for RTs were also examined with error rates. None of the comparisons

proved significant for error rates ( $P < 0.37$ ,  $P < 0.87$ ,  $P < 0.87$  and  $P < 0.61$  for the four comparisons, respectively).

## Discussion

This experiment extends previous *visual* studies that observed hemifield-wide distributions of covert attention (Hughes and Zimba 1985; Tassinari et al. 1987), or meridian effects (Rizzolatti et al. 1987; Gawryszewski et al. 1992; Reuter-Lorenz and Fendrich 1992), by adapting their design to study *auditory* performance. One would expect that a meridian effect should be observed within audition if this effect does indeed apply across modalities, as a strong version of premotor theory might suppose. However, the data provided no reliable evidence for a meridian effect.

There was a clear benefit for validly cued outer targets, compared with targets where the cue was invalid but appeared in the correct hemifield. This provides strong evidence against a simple hemifield-wide model for the effects of endogenous spatial attention on auditory performance, and is in accord with the gradient model of attention. The result demonstrates that covert attention may be endogenously focused within a hemifield, to affect auditory performance at one location within that hemifield differently than at another location on the same side.

The present experiment had used symbolic informative central cues, in order to induce a spatial expectancy about the likely lateral position of the upcoming auditory targets, and thus a shift of endogenous attention. Currently no information exists regarding the effects of attention within a hemifield on auditory performance when a purely *exogenous* attentional shift is induced (i.e. with peripheral but spatially non-predictive cues). Although the data collected from Experiment 1 suggest that endogenous control of spatial attention can benefit a particular lateral position within a hemifield in an auditory task, exogenous covert orienting of attention might, in principle, be more loosely focused for audition, reflecting a more primitive and reflexive system. In order to resolve this question, the second study examined the same issues as experiment 1, but now for the case of purely *exogenous* spatial attention effects on the same auditory task.

## Experiment 2

The design of this experiment was similar to experiment 1, except that spatially non-predictive peripheral auditory cues were now used, rather than predictive central cues. Each auditory target was now preceded by a non-imperative auditory cue. This came from the same lateral column of speakers as the subsequent target on 25% of trials, with the target appearing at one of the three remaining uncued columns for 75% of trials (i.e. 25% each). Many previous visual studies (e.g. Jonides 1976, 1981; Henderson 1991; Remington et al. 1992) have

shown that a salient peripheral visual cue can attract covert attention exogenously, even when not predictive of target location. Analogous exogenous spatial cueing effects have now been found for hearing also, with auditory peripheral cues followed by an auditory target. For instance, Spence and Driver (1994) found such an effect within the present up/down task, but they used only two rather than four columns of loudspeakers (i.e. one on each side), so that the distribution of spatial attention within a hemifield could not be examined. Here we used the same four-column arrangement as in experiment 1, but now with non-predictive peripheral auditory cues. This should allow determination of the distribution of *exogenous* covert attention in an auditory task, both between and within hemifields, for the first time.

## Materials and methods

### Subjects

Fourteen subjects participated. Three were unable to reach the 70% accuracy criterion. Of the remaining subjects, two were male and nine female. Their age ranged from 19 to 31 years, with a median age of 24, and all were right handed. Four had participated in experiment 1, but their results did not differ from those of the other subjects. All were naive as to the purpose of the experiment. The experiment required about 50 min, and the subjects were each paid £3.60 for their participation.

### Apparatus and materials

The set-up was identical to experiment 1 except for the cues, which were now peripheral, spatially non-predictive sounds, rather than central informative symbolic lights. The peripheral auditory cues were created by having both the upper and lower speakers at the cued eccentricity emit a 2000 Hz tone at 80 dB(A) for 100 ms. These high frequency cues can be localized by the human auditory system in azimuth, but not in elevation (Frens and Van Opstal 1994), and so cannot be used as local landmarks for the *elevation* discrimination of any target within the cued column of loudspeakers (see Spence and Driver 1994 for further discussion of this, and Spence and Driver 1997, for an empirical confirmation).

### Procedure

The procedure was similar to experiment 1, except for the probabilities of targets at each location, now following a peripheral cue. The 100 ms pure-tone cue was followed, at a stimulus onset asynchrony that varied randomly between 301–400 ms, by a white-noise auditory target with the same characteristics as in experiment 1. Regardless of which column the peripheral auditory cue was presented from, the auditory target was equally likely to come from any of the four loudspeaker columns. There were four possible cue locations and eight possible target locations, giving a total of 32 equiprobable cue-target combinations. Each block contained a total of 160 trials: five at each of the cue-target combinations. The order in which these 160 trials were presented was randomized between subjects. Subjects completed seven blocks, including the first practice block.

## Results

The data were collapsed across height (top and bottom targets) and side (left and right targets) as before. Trials

**Table 2** Mean reaction times (RT) and errors (%) for experiment 2

Target position		Valid hemifield cue		Invalid hemifield cue	
		Outer cue	Inner cue	Inner cue	Outer cue
Inside target	RT (ms)	501	486	495	505
	Errors (%)	9.9	11.3	12.2	11.7
Outside target	RT (ms)	525	547	546	545
	Errors (%)	10.0	11.2	9.4	10.2

in which the eye signal indicated a possible shift from fixation were excluded (10%, though note that most of these trials were due to blinks rather than overt eye movements). Trials with reaction times outside 150–1500 ms were also excluded (less than 1%). Mean reaction time data are presented in the *right* panel of Fig. 2, and both reaction time and error data are presented numerically in Table 2.

As in the previous experiment, a two-way ANOVA was conducted, with target location (two levels: inner, outer) and cue location (four levels) as within-subject factors. Inner targets were again responded to significantly more quickly than outer targets [ $F(1,10)=19.4$ ,  $P<0.001$ ; 497 versus 541 ms], reflecting the usual advantage for sounds more directly in front of the head (Moore 1985). There was a trend for an effect of cue location [ $F(3,30)=2.7$ ,  $P<0.06$ ]. Critically, a Target position by Cue position interaction was again found [ $F(3,30)=4.7$ ,  $P<0.001$ ], suggesting the presence of spatially specific cueing effects. The planned comparisons as described for experiment 1 (see schematics in Fig. 3) can again be used to test for hemifield, gradient and meridian effects.

The first comparison explores the hemifield-wide hypothesis for trials with outer targets, comparing valid cues versus invalid cues at the inner location in the correct hemifield (see Fig. 3A). This comparison proved to be significant [ $t(10)=2.7$ ,  $P<0.02$ , means of 525 versus 547 ms; the contrast remains significant at  $P<0.05$  one-tailed after Bonferroni correction]. Once again, this provides strong evidence against the Hughes and Zimba (1985) hemifield-wide hypothesis, now for the case of purely exogenous attention in an auditory task. The result demonstrates that covert attention can be exogenously focused within a hemifield to affect auditory performance differentially at different lateral positions on that side.

The second pairwise comparison (see Fig. 3B) also examines whether attention can produce effects on audition within a hemifield, now examining the case of an inner target either validly cued or invalidly cued by the outer location in the same hemifield. This comparison was not quite significant [ $t(10)=2.0$ ,  $P<0.08$ , in a two-tailed test], although the substantial trend was for subjects to respond faster to inner targets after a valid cue than after an invalid cue within the same hemifield (486 versus 501 ms).

The third planned comparison (see Fig. 3C) tested for a specific cost for crossing between hemifields, comparing trials where an inner target was invalidly cued either

by an outside cue in the correct hemifield, versus by an inner cue in the incorrect hemifield the same distance ( $34^\circ$ ) away from the target. The comparison did not approach significance [ $t(10)=0.6$   $P<0.52$ ]. This outcome is inconsistent with the hemifield-wide model, and suggests no meridian effect; indeed, any numerical trend was in the opposite direction to this prediction (501 ms for the invalid cues in the correct hemifield versus 495 ms).

The final planned comparison (see Fig. 3D) examines an outer target following an inner cue, in either the correct hemifield or the incorrect hemifield. Both the hemifield-wide model and any meridian effect suggest that a cue in the correct hemifield should facilitate performance more than a cue in the incorrect hemifield. Recall that a positive outcome for this comparison is not as telling as a positive result in the preceding comparison, because the two forms of invalid cue now have different distances from the target ( $34^\circ$  versus  $68^\circ$ ). Therefore, a positive finding would not necessarily be incompatible with other models of attention. However, a negative result in this comparison would be inconsistent with hemifield-wide theories and suggest no meridian effect. Analysis showed that there was no effect for this comparison [ $t(10)=0.1$ ,  $P<0.94$ ].

As in the earlier experiment, the error rate data were examined with a two-way ANOVA that had the same factors as used in the reaction time analysis. There was no main effect of target location [ $F(1,10)=0.1$ ,  $P<0.71$ ] or cue position [ $F(3,30)=0.8$ ,  $P<0.49$ ], and no interaction [ $F(3,30)=1.3$ ,  $P<0.30$ ]. The planned two-tailed  $t$ -test pairwise comparisons were also examined for error rates. None of the comparisons proved significant ( $P<0.50$ ,  $P<0.14$ ,  $P<0.10$  and  $P<0.18$  for the four comparisons, respectively).

Neither the reaction time nor the error data produced any evidence for “inhibition of return” (Posner and Cohen 1984) arising at the peripherally cued location. This effect is consistently absent in all previous cueing studies which used the present up/down task (e.g. see Spence and Driver 1994, 1996, 1997).

## Discussion

This study examined whether purely exogenous shifts of covert attention in an auditory task (i.e. following a peripheral auditory cue, that was spatially non-predictive concerning target location) can be accurately modeled

by the hemifield-wide, gradient, or premotor/meridian models for the spatial distribution of covert attention. Strong evidence was found against hemifield-wide activation, as in the previous endogenous experiment. For outer targets, there was an attentional advantage at the cued location relative to other locations *within* the cued hemifield; a similar (but less reliable) trend was apparent for inner targets. The peripheral auditory cue can thus lead covert attention to be focused within a hemifield to some extent (although this focus may be much broader than in a comparable visual study, given that audition has less spatial acuity).

As with experiment 1, these data reveal no clear evidence for any meridian effect in an auditory task. For the present case of purely exogenous peripheral cueing, this may not be in direct opposition to previous studies of the meridian effect in vision, as Rizzolatti et al. (1994) recently asserted that this effect may not operate following peripheral cues, being found in vision only following informative cues (see Rizzolatti et al. 1987; Umiltá et al. 1991; Reuter-Lorenz and Fendrich 1992).

## General discussion

Both the experiments presented here demonstrate that covert spatial attention can influence auditory performance, thus replicating and extending the findings of Spence and Driver (1994, 1996, 1997; see also Mondor and Zatorre 1995; Scharf 1998). Moreover, our experiments further demonstrate that covert attention can be focused on particular regions *within* a hemifield to affect auditory performance, thus falsifying any hemifield-wide account for attentional effects on audition. This conclusion was reached both for purely endogenous covert attention (experiment 1) and also for purely exogenous covert attention (experiment 2). The hemifield-wide model had not been addressed by most previous cuing studies with auditory tasks (e.g. Spence and Driver 1994, 1996, 1997), because these used only one possible eccentricity on each side. In both of the present experiments, an outer auditory target was responded to more quickly if the cue (be this a predictive central symbolic cue, or a nonpredictive peripheral cue) was valid than if the cue invalidly indicated the inner eccentricity within the same hemifield (comparison A; see the top panel of Fig. 3 and data for the corresponding conditions in Fig. 2). These studies thus show that covert attention can be narrowed to a specific eccentricity within a cued hemifield to affect auditory performance, not just to one entire side of space, in both the exogenous and endogenous case.

Recent research examining auditory event-related potentials (Teder-Sälejärvi and Hillyard 1998) also suggests that within-hemifield focusing of attention can affect audition for the endogenous case, finding that the amplitude of auditory evoked potentials are directly related to the separation between a sound and the current focus of endogenous spatial attention. The psychophysical data of Mondor and Zatorre (1995, experiment 4)

likewise suggest that within-hemifield focusing of attention can affect audition, although endogenous and exogenous attention could not be distinguished in their study (cues were not only informative, but also appeared directly at the potential target locations). Moreover, unlike the present study, eye position was not measured, and the results of Rorden and Driver (1999) show that this alone can be an important factor, which must be controlled before any effect can be unequivocally attributed to *covert* attention, as here.

No systematic difference was found between a validly cued inner target, versus an inner target cued by an outer position within the correct hemifield (at least, not for experiment 1, which involved endogenous attention; this comparison approached significance for the purely exogenous experiment 2). This pattern for inner targets might be interpreted in several ways, none of which requires the hemifield-wide account that was ruled out by the data from outer targets. One intriguing possibility is that attention might sweep across the inner target en route to the cued outer location, as suggested by analog-movement models that have been proposed in the past for visual attention (e.g. Shulman et al. 1979; Tsai 1983). In such a model, attention must be considered dynamically with respect to time. This could be examined further in the present auditory task, by varying cue-target stimulus onset asynchrony (SOA) extensively, in a paradigm otherwise similar to experiment 1. When the outer target is cued, analog-movement models of attention predict that the inner target on the cued side may show a benefit at the earlier SOAs, as attention sweeps across en route toward the cued outer location. On such models, the outer target should show specific benefits only at later SOAs, when attention finally reaches the distant outer location. However, it should be noted that the initial support for analog-movement models of covert attention in *visual* studies has been strongly challenged (see Cave and Bichot 1999). Moreover, some evidence already exists against this analog-movement notion for *auditory* attention also (see Mondor and Zatorre 1995).

A further possibility for how spatial cueing effects on auditory performance might unfold over time is that *both* eccentricities on the cued side may show an initial benefit, with the focus of attention then gradually narrowing to the cued eccentricity, rather than shifting across from central fixation in an analog manner (e.g. see related ideas from purely visual studies in Eriksen and Yeh 1985; Shepherd and Müller 1989; Umiltá et al. 1994). To explain the results of experiment 1, such a “zooming in” model would have to suppose that the narrowing rate has a different time-course for outer than inner targets, in order to produce the within-hemifield focusing that we found for the former but not the latter in our first study. Finally, it is possible that when expecting an outer target, subjects do not commit their attention as fully to the endogenously cued location as when expecting an inner target, perhaps because an outer target on one side is (on average) further away from all the other possible target locations than an inner target (Klein and McCormick 1989).

Our auditory experiments found no clear evidence for a meridian effect. Its absence in experiment 2 may have been due to the use of non-predictive peripheral cues, for which meridian effects are rarely found even in purely visual studies (Egly and Homa 1991; Reuter-Lorenz and Fendrich 1992; Rizzolatti et al. 1994). However, the design of experiment 1, with informative symbolic central cues, was closely modeled on Rizzolatti et al.'s (1987) classic design, which had demonstrated a clear meridian effect upon visual performance. While it is difficult to base a certain conclusion on negative results, the meridian effect does not appear to be a very robust factor for the effects of spatial attention on auditory performance, if it exists at all for this modality. This apparent difference between vision (where robust meridian effects have been reported) and audition (where they appear absent) may reflect a fundamental difference in the hard-wired structures for processing information in these two domains. In vision, information from distinct hemifields (upper and lower, as well as left and right) is processed in structurally distinct parts of the brain at several levels, as in many of the spatiotopic maps which exist in visual cortex. In contrast, the initial representations of auditory information are organized tonotopically, and likewise for some later cortical representations of sounds (e.g. Bilecen et al. 1998). One can speculate that the visual meridian effect may reflect the architecture of those anatomical structures which process specifically visual information, and which differ qualitatively from those for audition.

Although our experiments manipulated either just an auditory spatial expectancy about the likely location of sound targets (experiment 1), or else just the position of a non-predictive sound cue (experiment 2), one might argue that the observed effects on auditory performance need not reflect purely auditory attention, but instead crossmodal and/or visual attention. For instance, the experiments were not conducted in complete darkness, so subjects might have attended to the location of visible loudspeakers, which might in turn influence auditory performance via crossmodal mechanisms. We would not deny the existence of crossmodal links in spatial attention; indeed, we have argued extensively for them elsewhere (e.g. Driver and Spence 1994, 1998; Spence and Driver 1996, 1997; Rorden and Driver 1999). Nevertheless, the point still remains that no meridian effects were found for auditory performance here, neither following an auditory spatial expectancy, nor an auditory peripheral cue. Note also that if the effective attentional shifts in our studies had for some reason initially arisen within vision, and thereby produced a crossmodal effect upon auditory performance, this presumably should only have increased the likelihood of observing the meridian effects found for visual attention in the auditory task used here, yet none was observed.

In conclusion, the experiments presented here show that both exogenous and endogenous spatial attention can be focused within a hemifield to affect auditory performance. These results clearly rule out a hemifield-wide

model for spatial attention effects on audition. Of the different models considered, our findings appear most consistent with a gradient model for auditory effects (e.g. Mondor and Zatorre 1995).

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