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Head-centred meridian effect on auditory spatial attention orienting

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Six experiments examined the issue of whether one single system or separate systems underlie visual and auditory orienting of spatial attention. When auditory targets were used, reaction times were slower on trials in which cued and target locations were at opposite sides of the vertical head-centred meridian than on trials in which cued and target locations were at opposite sides of the vertical visual meridian or were not separated by any meridian. The head-centred meridian effect for auditory stimuli was apparent when targets were cued by either visual (Experiments 2, 3, and 6) or auditory cues (Experiment 5). Also, the head-centred meridian effect was found when targets were delivered either through headphones (Experiments 2, 3, and 5) or external loud-speakers (Experiment 6). Conversely, participants showed a visual meridian effect when they were required to respond to visual targets (Experiment 4). These results strongly suggest that auditory and visual spatial attention systems are indeed separate, as far as endogenous orienting is concerned.

Numerous studies have shown that individuals can focus their attention on a particular location without head or eye movements (i.e., covertly), and hence enhance the processing of stimuli occurring at that location. Indeed, the response to a target is faster and more accurate when it is presented at a previously cued location (i.e., on valid trials) than when it is presented at a previously uncued location (i.e., on invalid trials, Posner, 1978). Previous research provides also a distinction between endogenous and exogenous mechanisms of attention orienting. Exogenous mechanisms are under stimulus control and are induced by uninformative cues, which do not predict the target location but appear directly at it. Endogenous mechanisms of attention are under voluntary control and are induced by informative symbolic cues, such as numbers, that indirectly suggest the target location.

Although most studies investigated the orienting of attention in the visual modality, in recent years there has been a renewed interest in auditory selective attention, especially with

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regard to the mechanisms of auditory covert orienting. However, several issues are still a matter of debate. This paper is mainly concerned with the question of whether auditory and visual spatial attention are subserved by separate systems or by a unitary supramodal system. We provide evidence that visual and auditory attentional systems exist as separate entities by showing that each of them is associated with a different representation of space.

The general pattern of results from a number of studies on auditory attention orienting is quite similar to what has been reported in the visual modality. This similarity raised the question of whether or not separate spatial attention systems exist, one for the visual and one for the auditory modality, and how independent they are. Three general hypotheses may be addressed in this regard. The first one asserts that spatial attention is a supramodal function, subserved by anatomical circuits, which are separated from the data processing systems (e.g., Posner & Dehaene, 1994; Posner & Petersen, 1990). The second hypothesis holds that attention depends on the activity of the same circuits as those that process sensory data, without assuming any specific attentional circuit (e.g., premotor theory of attention, Rizzolatti & Camarda, 1987). In this case, spatial attention would be a consequence of the co-operative action of various pragmatic maps (e.g., oculomotor). According to this second hypothesis, spatial attention would be modality dependent, possibly showing different features for different sensory modalities. The third hypothesis is somewhat intermediate and holds that spatial attention is not completely independent from the sensory modality, but that the visual attention system dominates over the auditory attention system (Ward, 1994).

Evidence about this issue is rather controversial, and no definitive support exists for any hypothesis. Results supporting the supramodal hypothesis come from studies that showed that effects of visual and auditory covert orienting bear a strong similarity both in healthy individuals (e.g., McDonald & Ward, 1999; Mondor & Zattore, 1995; Rhodes, 1987) and in patients who had suffered damage to the right parietal lobe (e.g., Farah, Wong, Monheit, & Morrow, 1989). Indeed, Farah et al. concluded that parietal lobe mechanisms allocate attention to a supramodal representation of space. However, these findings are not compelling evidence for the supramodal hypothesis, because similarity of effects does not logically imply identity of mechanisms (e.g., see Spence & Driver, 1996). Consistently with the supramodal hypothesis, findings have also been reported that show that stimuli in one sensory modality attract attention to spatially coincident stimuli that appear subsequently in other modalities (McDonald, Teder-Sälejärvi, & Hillyard, 2000; McDonald & Ward, 2000). For instance, McDonald and Ward (2000) found that orienting spatial attention to an auditory stimulus modulates the event-related potentials to a subsequent visual target, but only after the initial stages of sensory processing are completed. Still, the possibility that individuals co-orient their visual and auditory attention to a common spatial location makes those results not completely unequivocal.

Another line of research was pursued by authors who investigated the cross-modal links between visual and auditory spatial attention. The supramodal hypothesis predicts that cueing effects—that is, the difference between reaction times (RTs) to valid and invalid trials—should also be observed when cues and targets are of different modalities, and that they should be equal in size to those observed when cues and targets are of the same modality. Results from this line of research are also not conclusive. For instance, Ward (1994) and Ward, McDonald, and Lin (2000) reported that visual cues affect both visual and auditory localization, but auditory cues affect only auditory localization. Ward concluded that these results were not consistent with the hypothesis of modality-specific attentional mechanisms and suggested that the visual spatial attention system dominates over the auditory spatial attention system. Interestingly, Spence and Driver (1997) reported the opposite pattern of results, but reached the same conclusions as Ward. In a series of experiments on exogenous mechanisms of cross-modal spatial attention, Spence and Driver (1997) found that auditory cues affected both visual and auditory target localization, whereas no sign of auditory orienting was found when visual cues were used. On the basis of these results, they concluded similarly to Ward that spatial attention is based on essentially visual mechanisms. Supposedly, the fact that both Ward (1997) and Spence and Driver (1997) reached similar conclusions from opposite results depends on the different mechanisms that they seem to invoke to explain cueing effects. According to Ward, cues activate a sort of spatial map, which in his interpretation is essentially a visual map. Auditory cues are able to activate a visual map, but when a conflict arises between cue and target, as in the auditory–visual cueing, then a series of computational steps are performed, which prevent any cueing effect from being apparent. Instead, according to Spence and Driver (1997), visual covert orienting tends to accompany covert auditory orienting, but not the reverse. These different conceptions about the effect of cueing on attentional orienting may explain why they reached the same conclusion on the basis of opposite results. This incongruence, however, also suggests a logical weakness inherent in using the possible links between cue and target modalities as a means of investigating the supramodal or modality-specific nature of attention orienting.

A number of later studies suggested that visual and auditory spatial attention systems work independently, at least in so far as exogenous mechanisms are concerned. For instance, Mondor and Amirault (1998) investigated both within-modal and cross-modal effects of peripheral uninformative and informative visual and auditory cues. They found that cue validity effects are larger when cues and targets belong to the same modality than when they belong to different modalities. According to Mondor and Amirault, these results suggest the existence of partially separated systems for auditory and visual attention in exogenous orienting. The rationale is that if the effect of spatial cues were mediated by a single system, then the modality manipulation would be irrelevant.

The clearest evidence about the independence of visual and auditory attention systems was provided by Spence and Driver (1996) who investigated the endogenous mechanisms of cross-modal attention. They devised a situation where a centrally presented cue indicated the likely location of target stimuli in one modality, whereas target stimuli in the other modality were more likely on the uncued side. Their results showed that the within-modality cueing effect was larger than the cross-modality effect. Once again, this difference was interpreted as suggesting that auditory and visual attention are served by partially independent systems. More importantly, Spence and Driver (1996) investigated whether individuals are able to simultaneously allocate visual and auditory attention to two opposite spatial locations. They did not find any reliable cueing effect when the spatial probabilities were indicated on a trial-by-trial basis. However, when the likely target side for each modality was held constant for each block of trials, significant cueing effects were found for both visual and auditory targets at the expected locations. This result suggests that the visual and auditory attention systems may work independently, as participants were able to attend to two different locations in two different modalities. Moreover, they also found that when the same side was most likely for both modalities, cueing effects were larger than when visual and auditory attention had to be directed to different sides. This last result is not consistent with the hypothesis of completely separated visual and auditory attention systems, and it led Spence and Driver (1996) to formulate their "separable-but-linked" hypothesis. However, the relevance of the results reported by Spence and Driver (1996) is undermined by the results reported by Eimer (1999), who failed to demonstrate that attention can be directed to opposite locations in different modalities, as far as attention orienting is indexed by event-related potentials. Moreover, findings reported by some authors (Awh & Pashler, 2000; Bichot, Cave, & Pashler, 1999; Hahn & Kramer, 1995) provide evidence that individuals are also able to attend to two non-contiguous spatial locations within a single modality (i.e., visually), under appropriate conditions. Evidently, if individuals are able to attend to different locations within a single modality, the fact that they are able to attend to different locations in different modalities cannot be considered conclusive evidence favouring the modality-specific hypothesis.

In summary, previous studies are still inconclusive as to whether the control of spatial attention operates in a supramodal or modality-specific fashion. For instance, evidence for cross-modal cueing effects may be considered as supporting the supramodal hypothesis, but may be accounted for by the modality-specific hypothesis as well, as individuals may co-orient their visual and auditory attention toward the cued location. Moreover, evidence that cross-modal and unimodal cueing effects are different in size may suggest that visual and auditory spatial orienting are served by separate systems, but because a cueing effect is present altogether, it remains to be established whether its reduced size is due to the difference in difficulty between the two conditions. The separate-but-linked hypothesis proposed by Spence and Driver (1996), on the other hand, is very interesting in its ability to account for a large number of empirical results, but still seems much too generic to represent a definitive solution, as it is not clear in which respect the two attentional systems are separate, how they are linked, and to what extent they are linked.

Less controversial conclusions could be drawn from evidence that the visual and auditory attention systems, if they do exist as separate entities, are differently and independently characterized with respect to some relevant feature or effect that is unrelated to individual's expectancies or tasks. One of these features might be represented by the meridian effects on visual spatial attention orienting (Hughes & Zimba, 1985, 1987; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). These effects have been fairly accounted for by the premotor theory of attention (Rizzolatti, Riggio, & Sheliga, 1994). Its general version holds that spatial selective attentional processes are embedded within cortical areas involved in programming motor actions related to specific sets of effectors. In other words, the attentional effects are due to the activity of the very same areas that subserve data processing or motor planning and execution. With this respect, the model predicts that systems underlying visual and auditory spatial attention are separate and independent of each other. Evidence in favour of the premotor theory of attention derives mainly from neuropsychological studies showing that the same structures involved in spatial attention are also involved in motor programming, as well as from psychological studies on attention orienting. The latter showed that when cued and target locations are on opposite sides of the vertical or horizontal visual meridians, reaction times to visual targets are slower than when they are on the same side of the visual meridians (Hughes & Zimba, 1985, 1987; Rizzolatti et al., 1987). According to the theory, the meridian effect is due to the updating of the oculomotor programme, which is needed when individuals have to redirect attention across visual horizontal or vertical meridians.

The visual meridian effect gives an interesting chance to further investigate the relationships between visual and auditory attention orienting. The supramodal and the visual attention dominance hypotheses lead to the prediction that a visual meridian effect would also be found when individuals are required to attend to auditory targets. Indeed, if one supramodal system existed that subserves attention orienting then one single representation of space would be likely to be used within that system. For the same reasons, if the visual system dominates over the auditory system then a visual representation of space would most likely be used in attention orienting in both vision and audition. On the other hand, if the visual and auditory attention systems were independent, then one would expect a different meridian effect on auditory orienting with respect to the visual one, due to the programming of a different set of effectors. Indeed, we expect that individuals show a head-centred meridian effect when orienting to auditory targets is required, because head movements and delays in arrival time to the two ears play an important role in auditory localization.

The aim of the following experiments was to investigate the effects of visual and head-centred vertical meridians in auditory orienting. In all the experiments except the first one, we used a general procedure aimed at dissociating the two vertical meridians. This was accomplished by requiring participants to maintain their head and body aligned to the centre of the monitor where cues were presented and to fixate their gaze to the right or to the left with respect to the centre of the monitor. In this way the vertical visual and head-centred meridians were not coincident, and their relative effects were investigated separately by comparing reaction times on trials where cued and target locations were separated by the visual meridian, the head-centred meridian, or no meridian at all. If different meridians were found to affect auditory and visual spatial orienting of attention, this would represent strong evidence favouring the modality-specific hypothesis.

It is important to note that the expected meridian effects cannot be accounted for by criterion shifts or overt attention orienting. Indeed, as all meridian-crossing trials were invalid, and their probabilities of occurrence were equated, there is no reason for criterion shifts to affect performance differently on different crossing conditions. By the same rationale, there is no reason why moving one's eyes toward the cued location should differently affect the response to targets appearing at different locations relative to the visual or head-centred vertical meridians. Indeed, overt orienting should lead to a linear increase in reaction times as a function of distance from the fixation point and not to visual or head-centred meridian effects. For these reasons, a detection task was used in Experiments 1–5, and eye movements were not monitored.

EXPERIMENT 1

The main goals of Experiment 1 were to test the validity of the general procedure to be employed throughout the following experiments, and to investigate further whether spatial attention orienting affects target detection operations in audition as well as in vision. Findings reported by several authors are not conclusive in this respect, as some of them showed that cueing effects are also apparent when individuals are required to detect auditory stimuli (e.g., Quinlan & Bailey, 1995), whereas others failed to observe any cueing effect on auditory target detection (e.g., Spence & Driver, 1994). Two main hypotheses may be advanced in this respect. The first one holds that the initial stages of information processing in hearing may be accomplished without any involvement of spatial attention, as peripheral levels of the auditory system lack a spatiotopic arrangement. The second hypothesis holds that detection tasks are usually much easier than localization or discrimination tasks, and that this is likely to make cueing effects much too small to be apparent. In this experiment, we asked participants to make a detection response to auditory targets that were delivered from four subjective spatial locations. This task should be more difficult than detecting auditory targets from only two opposite locations, as was usually the case in previous studies.

Method

Participants

A total of 15 individuals were recruited to participate in the experiment. Their mean age was 24.2 years, ranging from 20 to 30 years. All of them were undergraduate students and reported normal hearing and normal or corrected-to-normal vision. All participants were reported to be right handed, and were naive as to the purpose of the experiment. At a preliminary test, participants did not refer to any difficulty in hearing and localizing the auditory stimuli used throughout the experiment.

Stimuli

Target tones of 1000 Hz in frequency and 50 ms in duration were synthesized at a sampling rate of 22000 Hz. All tones were linearly tapered for 5 ms to eliminate onset and offset clicks. They were delivered through stereo-headphones at 40 dB SPL (between-channels average). The amplitudes of the right and left channels were varied in order to obtain four equidistant subjective spatial locations: at the left ear (position 0°); at 60° between the left ear and the vertex (position 60°); at 60° between the right ear and the vertex (position 120°); and at the right ear (position 180°). Even though the procedure used to vary the spatial location of the stimuli was rather crude, it was indeed effective, as reported by all the participants at a post-experiment interview.

The visual cue was a black rectangle that was presented on a light-grey background at one of four horizontally arranged and equidistant locations on a 14" computer monitor. Visual cues could appear at eccentricities of 3 and 9 degrees on the right and at eccentricities of 3 and 9 degrees on the left relative to the centre of the monitor.

As usual in cueing tasks, the cues could suggest the correct location of the incoming tone (valid trials) or not (invalid trials). In a different, neutral condition an uninformative central visual stimulus was presented instead of the spatially localized black rectangle.

Procedure

Participants were seated at a table, in a silent and dimly illuminated room, facing a computer monitor placed straight ahead with its centre at eye level. Their head movements were minimized by an adjustable chin rest. Participants were instructed to maintain their gaze on the fixation point at all times during each experimental session. The fixation point was a small cross constantly displayed at the centre of the monitor. Each trial of the experiment started with the appearance of the visual cue at one of the four locations on the screen, or at the centre of the screen in the neutral condition. After a mean delay of 1000 ms, ranging from 800 ms to 1200 ms, the auditory target was delivered at one of the four subjective locations. Participants were required to press a button held in their right hand as rapidly as possible in response to each target, regardless of its location. However, they were also informed that the visual cue suggested the most likely location of the incoming target. The visual cue remained on the screen until a response was made or for 1000 ms after the tone onset if no response was made. The time interval between two successive trials was 2500 ms.

This experiment comprised two blocks of 160 trials each. For all individuals, 75% of all trials had valid cues, 18.75% of all trials had invalid cues, and 6.25% of all trials had neutral cues. Trials were randomized within each block with the previous percentages. Participants were given a practice block of trials at the beginning of the experiment. Between the two experimental blocks, participants were allowed to rest for a few minutes.

Design

There were three conditions produced by the within-subjects factor of cue validity (valid, invalid, and neutral). Mean reaction times and proportion of errors were analysed through separate one-way analyses of variance (ANOVAs). Mean reaction times were computed for each experimental condition after having removed trials on which the response occurred before 100 ms from tone offset or after 800 ms from tone onset. Responses outside the acceptable range were considered as errors (anticipations and missing responses).

In order to exclude any bias due to the locations of the target tones, two further ANOVAs were carried out on the mean reaction times and on the proportion of errors on valid trials for each spatial location.

Results

On average, about 7% of trials were removed due to RTs falling outside the acceptable range. Mean instead of median RTs were computed for each participant because the different validity conditions had different probabilities of occurrence (Miller, 1988), with valid trials more likely.

ANOVAs failed to show any significant effect of spatial location on both proportions of errors (after arcsine transformation) and RTs to valid trials, $F(3, 42) = 1.03$, $p > .05$, and $F(3, 42) = 1.36$, $p > .05$, respectively. Analysis on RT data showed a significant effect of validity (valid, neutral, and invalid), $F(2, 28) = 4.28, p > .05$ (Geisser–Greenhouse epsilon = .93). Pairwise comparisons (Duncan's test) found that RTs were significantly faster for valid trials than for invalid trials (respectively, 220 ms and 233 ms, $p < .01$, Table 1). Mean RTs to neutral trials (229 ms) were between RTs to valid and invalid trials, but these differences were not statistically significant. An analogous analysis on error data (after arcsine transformation)

TABLE 1
Mean reaction times and mean proportions of errors as a function of cue validity in Experiment 1

	RT[a]		*Proportion of errors*	
Cue validity	*M*	*SD*	*M*	*SD*
Valid	219.97	52.16	.076	.069
Neutral	229.33	55.54	.084	.067
Invalid	233.18	60.61	.072	.072

[a] Reaction times, in ms.

did not show any effect of validity, $F(2, 28) = 1.37$, $p > .05$, indicating that there was no speed–accuracy trade-off accounting for the RT advantage when targets occurred at the cued location (Table 1).

Discussion

Results from Experiment 1 showed that mean reaction times to tones presented at the endogenously attended location were faster than reaction times to tones presented at the unattended locations. This validity effect was small but statistically reliable. These results confirm that participants can indeed orient their endogenous auditory spatial attention to a likely target location, as indicated by informative visual cues. It is noteworthy that a detection response was required in this experiment, confirming previous results (Quinlan & Bailey, 1995) that also showed reliable validity effects in simple detection tasks. Possibly, the use of detection tasks makes the validity effects of cueing on auditory target detection smaller in size and consequently more difficult to observe. However, in this experiment peripheral instead of central visual cues were used. With this experimental setting, exogenous effects of peripheral cues were probably present along with endogenous auditory orienting, with a reduction of the apparent size of endogenous cueing due to the inhibition of return (e.g., Itti & Koch, 2001). Indeed, the same pattern of results and about the same effect size was found by Quinlan and Bailey in their Experiment 1, in which peripheral auditory cues were used along with auditory targets. Interestingly, we observed a cueing effect of approximately the same size as that reported by Quinlan and Bailey even though we used a cross-modal paradigm, whereas they used both cues and targets in the auditory modality.

Conversely, in Experiment 1 no significant difference was found for valid and invalid trials compared to neutral trials—that is, no benefits or costs were found. Several authors failed to observe both benefits and costs with auditory targets, with some reporting costs but not benefits (Spence & Driver, 1996) and others reporting benefits but not costs (Bedard, El Massioui, Pillon, & Nandrino, 1993). The reason for this lack of consistency is not clear, but as a consequence of that, in many studies comparisons were made just between valid and invalid trials.

EXPERIMENT 2

The aim of Experiment 2 was to investigate whether auditory attentional orienting is affected by a head-centred or a visual meridian effect. As we argued earlier, the hypothesis that visual and auditory spatial attention are served by different systems would be supported by observing that reaction times to auditory stimuli on invalid trials are slower when cued and target locations are on opposite sides of the head-centred meridian than when they are on opposite sides of the visual meridian. On the other hand, both the supramodal hypothesis and the visual dominance hypothesis predict that a visual meridian effect should be apparent also when individuals are required to respond to auditory targets. In order to test the two meridian effects independently, we required participants to maintain their head aligned to the centre of the visual display where cues were presented and to fixate their gaze to a fixation point shifted rightward or leftward with respect to the head midline. By this arrangement, the visual vertical meridian and the head-centred vertical meridian were dissociated.

Method

Participants

The same volunteers as those in Experiment 1 also participated in Experiment 2, which was run immediately after Experiment 1.

Procedure

Stimuli and procedure were identical to those used in Experiment 1. The only exception was the position of the fixation point, which was shifted between locations 9° left and 3° left (on half of the trials) or between locations 9° right and 3° right (on the remaining trials) of the monitor (see Figure 1). Head position was held aligned to the centre of the monitor and was maintained by means of an adjustable chin rest. The body was also aligned with the head. With this arrangement, a dissociation between the visual and head-centred meridians was achieved. The visual vertical meridian was located between positions 9° left and 3° left or between 9° right and 3° right, depending on the block of trials, whereas the head-centred vertical meridian was always located between positions 3° left and 3° right. Hence, on invalid trials participants had to shift their attention from the cued location to the target location, and they could cross the visual vertical meridian, the head-centred vertical meridian, or no meridian at all, depending on the specific locations. Distances between the cued and target locations were made equal across the three conditions. Invalid trials belonging to each of the three conditions (visual meridian crossing, head-centred meridian crossing, no crossing) comprised 6.25% of all trials. Participants were given a practice block of trials at the beginning of the experiment and were allowed to rest for a few minutes between the two experimental blocks.

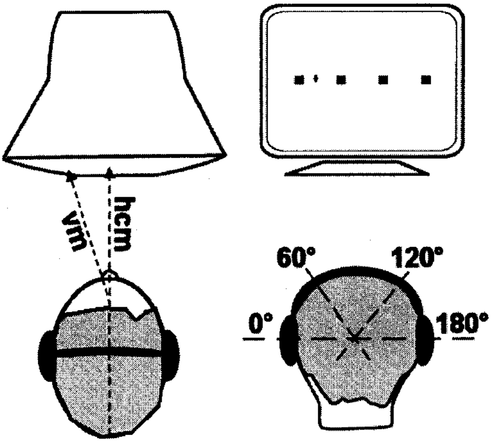

Figure 1. Relative arrangement of visual cues, locations of auditory targets, and observers' head and gaze positions in Experiments 2–3. In Experiment 2 the visual cue was a small rectangle appearing at one of four evenly spaced locations on the screen, as depicted in the left panel. In Experiment 3 the visual cue was a number (from 1 to 4) appearing at the same location as that of the fixation point. In both Experiments 1 and 2 the auditory targets were delivered through headphones at the locations depicted in the right panel. The observers had their head aligned with the centre of the screen, but their gaze fixed on the off-centre fixation point (left panel). vm: visual meridian. hcm: head-centred meridian.

Design

Three conditions were produced by the within-subjects factor of cue validity (valid, invalid, and neutral), and three conditions were produced by the within-subjects factor of meridian crossing (visual meridian crossing, head-centred meridian crossing, no crossing). Mean reaction times and proportion of errors were analysed through separate one-way ANOVAs for the cue validity and meridian-crossing factors. Mean reaction times were computed for each experimental condition after having removed trials on which a response occurred before 100 ms from tone offset or after 800 ms from tone onset. Also in this experiment, the equivalence of the locations of the target tones was tested through two separate ANOVAs on mean reaction times and on proportion of errors on valid trials for each spatial location.

Results

In Experiment 2, about 15% of trials were removed due to RTs falling outside the acceptable range. ANOVAs failed to show any significant effect of spatial location on both proportions of errors (after arcsine transformation) and RTs to valid trials, $F(3, 42) = 0.53$, $p > .05$, and $F(3, 42) = 0.59$, $p > .05$, respectively. The results confirm the absence of any bias due to the stimuli or their locations. Analysis on RT data showed a significant effect of validity (valid, neutral, and invalid), $F(2, 28) = 4.23$, $p > .05$ (Geisser–Greenhouse epsilon = .96). Duncan testing showed that RTs were significantly faster for valid trials than for both invalid and neutral trials ($p < .05$, Table 2). No difference was found between RTs for neutral and invalid trials, showing that benefits were associated with attention orienting, but not costs. A similar analysis on error data (after arscine transformation) did not show any effect on validity, $F(2, 28) = 1.44$, $p > .05$, indicating that there was no speed–accuracy trade-off that could account for the RT advantage when the target occurred at the cued location.

The analysis of RTs to invalid trials showed a significant effect of meridian crossing, $F(2, 28) = 3.44$, $p > .05$ (Geisser–Greenhouse epsilon = .82). Duncan's test showed that RTs were significantly slower for invalid trials where attention had to be moved across the head-centred vertical meridian than for invalid trials where attention had to be moved for an equal distance without crossing any meridian (Table 2). RTs on invalid trials in which attention had to be shifted across the visual vertical meridian were intermediate and not significantly different from RTs on the other two conditions. A similar analysis on arcsine transformation of proportions of errors revealed a significant effect of meridian crossing, $F(2, 28) = 3.91$, $p < .05$ (Table 2). Duncan's test showed that participants made more errors when cued and target locations were separated by the head-centred meridian than when cued and target locations were separated by the visual meridian or by no meridian at all ($p < .05$ in both cases, Table 2). This pattern of results is not compatible with a speed–accuracy trade-off account of the cost due to the crossing of the vertical head-centred meridian.

Discussion

Results from Experiment 2 confirm first of all that auditory attention can be oriented to spatially separated locations and also significantly affects simple processes such as target detection operations. The difference between RTs on valid and invalid trials was small but significant, as was found in our Experiment 1 and by Quinlan and Bailey (1995). This confirms

TABLE 2
Mean reaction times and mean proportion of errors as a function of cue validity and meridian crossing in Experiment 2

		RT[a]		*Proportion of errors*	
Condition		*M*	*SD*	*M*	*SD*
Cue validity	Valid	205.79	53.96	.15	.14
	Neutral	215.76	64.57	.17	.15
	Invalid	216.96	64.06	.15	.15
Meridian crossing	Visual	215.89	63.29	.14	.21
	Head centred	222.01	66.87	.21	.17
	No crossing	209.23	59.53	.13	.15

[a] Reaction times, in ms.

that the use of a detection task makes the effects of cueing on auditory target detection smaller in size, but reliable. Also, results from Experiment 2 suggest that neutral trials are more difficult to consider than is usually reported in visual attention studies. In Experiment 1, RTs on neutral trials were intermediate between RTs on valid and invalid trials, Experiment 2 RTs on neutral trials were significantly different from those on valid trials and almost identical to those on invalid trials. The heterogeneity of the effects involving neutral trials suggests that the operations that individuals carry out during these trials are far from being clear and definite. Also, individuals made more errors in Experiment 2 than in Experiment 1. However, the difference is small in absolute terms, so it is likely to be due to chance, or to the more comfortable position of the participants during Experiment 1.

With regard to the main hypothesis of Experiment 2, the results showed evidence for a meridian effect, which seems to depend on the head-centred meridian rather than on the visual meridian. Reaction times were significantly slower when visual cues and target tones were separated by the vertical head-centred meridian than when they were not separated by any of the two meridians, distances being equal. Reaction times on trials in which the target cues were separated by the visual meridian were intermediate, but not significantly different from any of the others. This pattern of results clearly precludes any inference regarding the effect of the visual meridian. However, as the only significant effect regarded the head-centred meridian, the overall pattern suggests that the role played by the visual meridian in the visual modality is played by the head-centred meridian in the auditory modality. If confirmed, this result would have some relevant implications both for the premotor theory of attention and for the question of whether separate attentional systems exist for vision and audition.

It should be stressed that even though the use of a detection task makes an analysis on d' and β impossible, criterion shifts cannot account for the slower reaction times on invalid trials that imply a crossing of the head-centred meridian than on trials that imply a crossing of the visual meridian or no crossing at all. Indeed, as all those trials were invalid, and their probabilities of occurrence were equated, there is not reason for a criterion shift to occur.

EXPERIMENT 3

Results of Experiment 2 suggest that auditory and visual spatial orienting show different features, at least in so far as mechanisms underlying meridian effects are concerned. This finding is in clear agreement with the hypothesis that visual and auditory spatial attention rely on separate systems. However, even though the effect of the head-centred meridian crossing was significant, it was also small in size. The small effect size of meridian crossing might be due to the use of peripheral instead of central cues. In these conditions, both endogenous and exogenous orienting mechanisms are probably called into play, producing a reduced net effect on RTs on invalid trials due to the inhibition of return. Although the use of peripheral cues might represent a "conservative" approach that protects against false positive results, it may also raise a problem of statistical power. In order to confirm that the meridian effect in auditory spatial attention orienting is based on the head-centred meridian, we replicated Experiment 2 with central visual cues. In these conditions, as only endogenous orienting mechanisms should be involved, a larger effect on RTs on crossing trials is expected. Furthermore, in order to investigate the effect of physical features of auditory stimuli on auditory orienting, we used pure tones at two different frequencies.

Method

Participants

A total of 14 undergraduates volunteered for this experiment. They ranged in age from 20 to 30 years, with a mean age of 22.6 years. All participants reported normal hearing and normal or corrected-to-normal vision and were naive as to the purposes of the study and the experimental procedures. In a preliminary test, participants did not refer to difficulties in hearing and localizing the auditory stimuli used throughout the experiment. Moreover, none of these volunteers had participated in the previous experiments.

Stimuli and procedure

Target tones of 1000 Hz and 800 Hz were synthesized at a sampling rate of 22000 Hz. All tones were 50 ms long and were linearly tapered for 5 ms to eliminate onset and offset clicks. They were delivered through stereo-headphones at 40 dB SPL (between-channels average) with a 16-bit output resolution. As in the previous experiments, the subjective locations of the tones were induced by varying the amplitudes of the right and left channels of the headphones. Subjective locations were the same as those used before (0°, 60°, 120°, and 180°, relative to the left ear).

In this study, central rather than peripheral informative visual cues were used. Cues were the digits from 1 to 4 and were displayed on the computer monitor at the same location as that of the fixation point. They indicated the four possible locations of the auditory targets, the digit 1 corresponding to the leftmost location and the digit 4 corresponding to the rightmost location. The neutral uninformative cue was a small rhombus displayed at the same location as that of the informative cues.

In order to dissociate the effects of the visual and head-centred meridians, the same general procedure as that in Experiment 2 was adopted also in this study (Figure 1). Experiment 3 comprised four blocks of 160 trials each. The percentage of valid trials with respect to the invalid trials was 75%.

Design

In Experiment 3 there were 3 by 2 conditions produced by the within-subjects factors of cue validity (valid, invalid, and neutral) and frequency of tone (1000 Hz and 800 Hz), and 3 by 2 conditions produced by the within-subjects factors of meridian crossing (visual meridian crossing, head-centred meridian crossing, no crossing) and tone frequency. Mean reaction times and error rates were analysed through separate two-way ANOVAs for the cue validity and meridian-crossing factors. Mean reaction times were computed for each experimental condition after having removed trials on which the response occurred before 100 ms from tone offset or after 800 ms from tone onset.

In order to exclude any bias due to the locations of the target tones, two separate ANOVAs were carried out on the mean reaction times and on the number of errors on valid trials for each spatial location and tone frequency.

Results

On average, RTs fell outside the acceptable range on about 19% of trials and were removed. ANOVA failed to show significant main effects of spatial location and frequency or significant interactions between location and frequency on the proportions of errors to valid trials (after arcsine transformation), $F(3, 39) = 0.68$, $p > .05$, $F(1, 13) = 0.70$, $p > .05$, and $F(3, 39) = 0.42$, $p > .05$, respectively. Also, no main effect of spatial location and frequency or their interaction was found on RTs to valid trials, $F(3, 39) = 1.90$, $p > .05$, $F(1, 13) = 0.38$, $p > .05$, and $F(3, 39) = 0.46$, $p > .05$, respectively. These results confirm that biases due to the stimuli or their locations were not present.

Analysis of RT data showed a significant main effect of validity (valid, neutral, and invalid trials), $F(2, 26) = 8.91$, $p > .001$ (Geisser–Greenhouse epsilon = .98). Pairwise comparisons (Duncan's test) showed that RTs were significantly slower for invalid trials than for both valid and neutral trials ($p < .003$ in both cases, Table 3). No difference was found between RTs on neutral and valid trials. There was no significant main effect of frequency, $F(1, 13) = 0.82$, $p > .05$, and no significant interaction between validity and frequency, $F(2, 26) = 0.78$, $p > .05$. A similar analysis on error data (after arcsine transformation) showed a main effect of frequency, $F(1, 13) = 8.60$, $p > .01$. Participants made more errors to 1000 Hz tones than to 800 Hz tones (Table 3). There was no effect of validity, $F(2, 26) = 1.35$, $p > .05$, and no significant interaction between validity and frequency, $F(2, 26) = 2.1$, $p > .05$, indicating that speed–accuracy trade-off cannot account for the RT advantage when the target occurred at the cued location.

The analysis of RTs to invalid trials showed a significant effect of meridian crossing, $F(2, 26) = 8.61$, $p < .001$ (Geisser–Greenhouse corrected $p < .01$, epsilon = .68). Duncan testing showed that RTs were significantly slower on invalid trials on which attention had to be moved across the head-centred vertical meridian than on invalid trials on which attention had to be moved across the visual meridian ($p < .01$) or without crossing any meridian ($p < .01$, Table 3). There was no significant main effect of frequency, $F(1, 13) = 3.19$, $p > .05$, and no significant interaction between meridian crossing and frequency, $F(2, 26) = 0.48$, $p > .05$ (Table 3).

The same analysis on arcsine transformation of proportions of errors revealed only a marginally significant main effect of frequency, $F(1, 13) = 3.19$, $p = .06$, due to the slightly larger proportion of errors to 1000 Hz tones than of those to 800 Hz tones. There was no

TABLE 3
Mean reaction times and mean proportion of errors as a function of cue validity, frequency, and meridian crossing in Experiment 3

		Frequency[b]							
		1000				*800*			
		RT[a]		*Proportion of errors*		*RT*[a]		*Proportion of errors*	
Condition		*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Cue validity	Valid	231.36	71.80	.20	.18	233.10	68.78	.17	.14
	Neutral	245.51	80.52	.27	.27	245.88	77.54	.20	.18
	Invalid	275.42	83.06	.19	.16	284.39	89.42	.13	.14
Meridian crossing	Visual	246.98	68.28	.22	.21	257.28	71.50	.17	.21
	Head-centred	284.68	98.21	.16	.21	300.60	107.37	.13	.16
	No crossing	249.36	81.78	.23	.20	255.50	80.90	.17	.19

[a] Reaction times, in ms.
[b] In Hz.

significant main effect of the crossing condition, $F(2, 26) = 1.54$, $p > .05$, and no significant interaction of crossing and frequency, $F(2, 26) = 0.91$, $p > .05$ (Table 3). This pattern of results is not compatible with a speed–accuracy trade-off accounting for the cost due to the crossing of the vertical head-centred meridian.

Discussion

Results from Experiment 3 confirm and extend those of Experiment 2. The difference between RTs on valid and those on invalid trials was larger than the difference found in Experiments 1 and 2 (about 60 ms, collapsed across frequencies). This finding was of course expected, for it is well known that central "cognitive" cues lead to larger cueing effects in spatial priming tasks. Moreover, results showed again the presence of a head-centred meridian effect on RTs on invalid trials. Indeed, participants' responses were significantly slower when visual cues and target tones were separated by the vertical head-centred meridian than when they were separated by the visual meridian or by no meridian.

These results seem relevant from several points of view. First of all they may be considered as supporting the premotor theory of attention, but only in its general formulation. As previously noted, whereas the theory asserts that attention is due to the activity of any motor system, empirical studies concentrated upon the visual system by claiming that it is dominant upon any other one. If this version of the theory was true, then a visual meridian effect should also have been observed with auditory targets, contrary to what was found in this experiment. It should also be noted that because of the arrangement used here, trials on which individuals had to shift attention across the head-centred meridian do not require any reprogramming of the direction of the ocular movement. This suggests that the head-centred meridian effect cannot be accounted for by any oculomotor re-programming.

Second, and more important, these results strongly suggest that different representations of space are involved in endogenous orienting of auditory and visual attention, contrary to what any supramodal theory would predict. Indeed, although a supramodal attention system appears physiologically plausible, its engagement should, however, elicit the same meridian effect in visual as that in auditory orienting of attention. On the other hand, in previous experiments we did not actually test the visual meridian effect on visual target detection. This fact leaves the possibility open that the visual meridian effects are due to the position of the head and not to any oculomotor programme. If this were true, then the head-centred meridian effect that we found would not be specific to auditory attention orienting, and its value as evidence favouring the modality-specific hypothesis of spatial attention would be compromised.

EXPERIMENT 4

Experiment 4 was designed to test the hypothesis that the head-centred meridian effect on RTs to auditory targets reflects a more general effect due to the position of the head and is not specific to the auditory orienting of attention. This hypothesis seems quite unlikely, as it would be at odds with any account for the visual meridian effect based on the premotor theory of attention. Indeed, oculomotor reprogramming cannot explain the effect of the head-centred meridian that we found in the previous experiments, because no change of the direction of the ocular movement is required when the cued and the target locations are on opposite sides of this meridian. However, data reported in the literature do not allow us to rule out this hypothesis. Interestingly, to our knowledge in all the studies aimed at investigating the visual meridian effect on RTs to visual targets, participants' head and gaze were always aligned to the centre of the screen where the target stimuli appeared. This arrangement made it impossible to disentangle the effects of the two meridians and hence to demonstrate that the visual meridian effect is associated with oculomotor programme updating.

In Experiment 4, the same general procedure was used as that in the previous experiments, but participants were required to detect visual targets presented at four spatial locations distributed across the visual and the head-centred meridians. If the effect of the visual meridian is specific to visual orienting of attention, we should expect slower reaction times to visual targets when cued and target locations are opposite with respect to the fixation point than when they are opposite with respect to the head midline.

Method

Participants

A total of 15 undergraduate volunteers took part in Experiment 4. They ranged in age from 20 to 30 years, with a mean age of 24.3 years. All participants had normal or corrected-to-normal vision and were naive as to the purpose of the study and the experimental procedures. None of them had participated in the previous experiments.

Stimuli

The stimuli were presented on a 14" colour monitor placed 50 cm from the participant. Each trial started with the presentation of a cue (either a digit from 1 to 4, or a black square about 0.6° in height), which replaced the fixation point. The cue was followed by a target, which was a grey rectangle 0.6° × 0.8° in size. Target stimuli could appear at four possible locations, 7° apart (centre to centre), arranged in a row along the horizontal meridian, two on the left and two on the right of the geometrical centre of the screen. The informative cues indicated the locations of the incoming targets, the digit 1 corresponding to the leftmost location and the digit 4 corresponding to the rightmost location. The neutral cue (the black square) did not indicate any particular location. Participants were informed about the possible locations of the target stimuli, but no visual demarcation of them was provided during the experiment. The fixation point was a small cross (0.6° × 0.6°) presented either at 7° on the left (i.e., between Locations 1 and 2, on half of the trials) or at 7° on the right (i.e., between Locations 3 and 4, on the remaining trials) of the geometrical centre of the screen. As usual, the visual cue correctly indicated the location of the incoming target on valid trials, whereas on invalid trials it indicated one of the three locations different from that of the incoming target, with the same probability of occurrence. On neutral trials, the neutral cue was presented.

Procedure

The same general procedure as that in Experiment 3 was adopted in this experiment. Participants were required to maintain their gaze on the fixation point, while the head position was held aligned to the centre of the screen through a head-and-chin rest. The body was also aligned with the head. With this arrangement, the visual and head-centred vertical meridians were dissociated, as usual. Each trial started with the appearance of the visual cue, which replaced the fixation point. After a mean delay of 1000 ms, the visual target was presented for 100 ms at one of the four locations. Participants were required to press a push button held in their right hand as fast as possible to each target, irrespective of its location. They were also informed that the cue suggested the most likely location of the incoming target so that the best strategy to achieve a fast response was to allocate their attention to the cued location. The cue remained on the screen until a response was made or for 1000 ms after the target onset if no response occurred. The time interval between two successive trials was 2500 ms. This experiment comprised six blocks of 160 trials each. The percentage of valid trials was 75%. With this experimental setting, the shifting of attention on invalid trials could imply the crossing of the visual vertical meridian (e.g., when the fixation point was on the left, the cue was the digit 1, and the target was at Location 2), the crossing of the head-centred vertical meridian (e.g., when the cue was the digit 2, and the target was at Location 3), or no crossing (e.g., when the cue was the digit 3, and the target was at Location 4).

The design for previous experiments was adopted in Experiment 4.

Results

On average, about 9% of trials were removed due to RTs falling outside the acceptable range. ANOVAs failed to show any significant effect of spatial location on both proportion of errors (after arcsine transformation), $F(3, 42) = 0.86$, $p > .05$, and RTs on valid trials, $F(3, 42) = 1.22$, $p > .05$. These results confirm that there was not any bias due to the targets and locations. Analysis on RT data showed a significant effect of validity (valid, neutral, and invalid), $F(2, 28) = 10.40$, $p < .001$ (Geisser–Greenhouse epsilon = .8). Pairwise comparisons (Duncan's test) showed that RTs were significantly slower on invalid trials than on both valid and neutral trials ($p < .01$ in both cases, Table 4). No difference was found between RTs on

TABLE 4
Mean reaction times and mean proportion of errors as a function of cue validity and meridian crossing in Experiment 4

Condition		*RT*[a] *M*	*RT*[a] *SD*	*Proportion of errors* *M*	*Proportion of errors* *SD*
Cue validity	Valid	227.80	36.16	.08	.11
	Neutral	232.18	41.80	.11	.08
	Invalid	246.48	34.45	.10	.12
Meridian crossing	Visual	255.95	33.92	.09	.10
	Head centred	232.91	38.15	.08	.09
	No crossing	235.84	31.50	.10	.12

[a] Reaction times, in ms.

neutral and valid trials, showing that costs were associated with attention orienting but benefits were not. A similar analysis on error data (after arcsine transformation) did not show any effect of validity, $F(2, 28) = 1.52$, $p > .05$, indicating that there was no speed–accuracy trade-off accounting for the RT advantage when the target occurred at the cued location.

The analysis of RTs to targets presented on invalid trials showed a significant effect of meridian crossing, $F(2, 28) = 9.14$, $p = .001$ (Geisser–Greenhouse epsilon = .87). Duncan's test showed that RTs were significantly slower on those invalid trials on which attention had to be shifted across the visual vertical meridian than on invalid trials on which attention had to be shifted across the head-centred meridian ($p < .001$) or without crossing any meridian ($p < .01$, Table 4), distances between cued and target locations being equal.

A similar analysis on arcsine transformation of proportions of errors failed to reveal a significant effect of meridian crossing, $F(2, 28) = 0.70$, $p > .05$ (Table 4). This pattern of results is not compatible with a speed–accuracy trade off accounting for the cost due to the crossing of the visual meridian.

Discussion

Results of Experiment 4 confirm that the meridian effect on reaction times to visual targets is indeed associated with the visual meridian and does not depend on a general effect of the head position. In fact, participants were slower when the target appeared at an uncued location opposite to the cued location relative to the visual meridian than when it appeared at an uncued location opposite the cued location relative to the head-centred meridian. This finding is supported by the absence of any effect of crossing on error rates, which rules out any speed–accuracy trade-off accounting for the visual meridian effect. The pattern of results of Experiment 4 supports the hypothesis that visual covert orienting is strictly linked to the oculomotor programme needed to make a saccade toward the cued location. This evidence is particularly important as it is not confounded due to the coincidence of visual and head-centred meridians that made findings of previous experiments relatively ambiguous.

These results also rule out any accounting for the head-centred meridian effect on reaction times to auditory targets based on some artefacts due to the particular experimental setting, for instance to the procedure that we used to dissociate the visual and head-centred vertical meridian. Except for the target sensory modality, the apparatus and procedure were identical to those used in Experiments 2 and 3. Moreover, the results of Experiment 4 support the hypothesis that the effect of the head-centred meridian on reaction times to auditory targets is specific to auditory orienting.

EXPERIMENT 5

Results of Experiment 1 to 3 strongly suggest that individuals are indeed able to allocate their auditory attention to a previously cued location, and that in doing so they use an auditory spatial representation that seems to depend on a head-centred spatial frame of reference. However, we have to note that cross-modal cueing procedures were used in previous experiments, as visual stimuli cued the most likely location of the incoming auditory targets. Whereas it is rather unlikely that the effect of the head-centred meridian appears only in cross-modal conditions, this possibility cannot be ruled out only on the basis of previous empirical findings. Indeed, neurophysiological data about the links between oculomotor and auditory systems within the superior colliculus might suggest that a reduction of the visual meridian effect occurs when individuals auditorily attend to a visually cued location. The superior colliculus plays an important role in initiating saccades (Moschovakis, 1996), and the receptive fields of neurons discharging prior to saccadic eye movement are in a spatiotopic register with the receptive fields of both visual and auditory sensory neurons (Jay & Sparks, 1987; Palmer & King, 1982). These neurons integrate afferent activity from different modality-specific pathways, and their responses to multimodal signals may be substantially greater, due to summation effects, than their responses to the individual unimodal components (Meredith & Stein, 1986). It has also been found that those summation effects depend on the spatial alignment between the auditory and visual stimuli, because their misalignment reduces the latencies of saccadic eye movements without affecting their amplitude (Hughes, Nelson, & Aronchick, 1998). By considering these effects, one might speculate that when a visual cue and an auditory target are presented on invalid trials in an attention-orienting task, then a reduction of the visual meridian effect due to the saccade motor programme reorienting will occur, possibly leading to the appearance of a head-centred meridian effect. In order to control for this hypothesis, we conducted a further experiment in which cue and target stimuli were auditorily presented. If the head-centred meridian effect was due to the misaligned visual cue and auditory target occurring on invalid trials, then the same effect should not be evident in this unimodal condition.

Method

Participants

A total of 13 undergraduate volunteers took part in Experiment 5. They ranged in age from 20 to 30 years, with a mean age of 23.8 years. All participants had normal hearing and were naive as to the purpose of the study. At a preliminary test, participants were able to hear and localize correctly the auditory stimuli used throughout the experiment. None of them had participated in the previous experiments.

Stimuli and procedure

In Experiment 5, the target stimuli, the procedure, and the design of analysis were identical to those used in Experiment 3. The only exception regarded the cues that were auditorily presented. Cues were the digits from 1 to 4 and the digit 6 pronounced by a male voice and recorded on disk after being sampled at 44000 Hz. All the voice recordings were processed in order to have a duration of 300 ms. They were delivered through stereo-headphones, as well as the target stimuli, at 60 dB SPL with a 16-bit output resolution. As in Experiment 3, the cues suggested the four possible locations of the auditory targets (Figure 1), the digit 1 corresponding to the leftmost location and the digit 4 corresponding to the rightmost location. The neutral cue was the digit 6. Target stimuli were the 1000-Hz tones used in Experiment 3. This experiment comprised four blocks each of 150 trials. The percentage of valid trials with respect to the invalid trials was 76%. As usual, on invalid trials participants were requested to shift their covert attention from the cued position to the position where the tone occurred. This shifting could imply the crossing of visual vertical meridian (e.g., when the cue was the digit 1, and target was delivered at 60°), the crossing of the head-centred vertical meridian (e.g., when the cue was the digit 2, and the target was in position 120°), or no crossing (e.g., when the cue was the digit 3, and the target was in position 180°.

Results and discussion

On average, about 22% of trials were removed due to RTs falling outside the acceptable range. ANOVAs failed to show any significant effect of spatial location on both proportion of errors (after arcsine transformation), $F(3, 30) = 1.28$, $p > .05$, and RTs on valid trials, $F(3, 30) = 0.81$, $p > .05$. As in previous experiments, these results show that there was no effect due to targets and locations.

Analysis of RT data showed a significant effect of validity (valid, neutral, and invalid), $F(2, 20) = 5.02$, $p < .05$ (Geisser–Greenhouse epsilon = .68). Pairwise comparisons (Duncan's test) showed that RTs were significantly faster on valid trials than on both invalid and neutral trials ($p < .05$ in both cases, Table 5). No difference was found between RTs on neutral and invalid trials, showing that benefits were associated with orienting of attention but costs were not.

TABLE 5
Mean reaction times and mean proportion of errors as a function of cue validity and meridian crossing in Experiment 5

		RT[a]		*Proportion of errors*	
Condition		*M*	*SD*	*M*	*SD*
Cue validity	Valid	222.54	33.23	.23	.23
	Neutral	231.69	30.12	.23	.24
	Invalid	233.04	32.20	.19	.22
Meridian crossing	Visual	225.51	36.62	.23	.24
	Head centred	247.05	40.17	.22	.23
	No crossing	226.85	27.88	.22	.23

[a] Reaction times, in ms.

A similar analysis on error data (after arcsine transformation) showed a significant effect of validity, $F(2, 20) = 6.07$, $p < .01$. Duncan's test showed that participants made significantly fewer errors on neutral trials than on both valid and invalid trials ($p < .01$, in both cases). However, no difference was found between error rates on valid and invalid trials leading to the conclusion that any cueing effect was not due to a change in decision criterion.

The analysis of RTs to targets presented on invalid trials showed a significant effect of meridian crossing, $F(2, 20) = 5.36$, $p < .05$ (Geisser–Greenhouse epsilon = .86). Duncan's test showed that RTs were significantly slower on invalid trials in which attention had to be shifted across the head-centred meridian than on invalid trials in which attention had to be shifted across the visual meridian ($p < .01$) or without crossing any meridian ($p < .05$, Table 5) distances between cued and target locations being equal.

A similar analysis on arcsine transformation of proportions of errors failed to reveal a significant effect of meridian crossing, $F(2, 20) = 0.28$, $p > .05$ (Table 5). This pattern of results is not compatible with a speed–accuracy trade-off accounting for the cost due to the crossing of the head-centred meridian. As a head-centred meridian effect was also found when cues and target were both auditorily delivered, it is possible to reject the hypothesis that the head-centred meridian effect was due to the faster saccade programme execution occurring when stimuli of different modalities are spatially misaligned. This confirms that the head-centred meridian effect is specific to auditory orienting of attention, and suggests that individuals make use of different representations of space when required to attend to auditory or visual stimuli.

EXPERIMENT 6

Results of Experiments 1–5 might be difficult to generalize because auditory targets were delivered through headphones rather than through external loudspeakers. In the reviewing process of the present paper Ward proposed the interesting hypothesis that in previous experiments a head-centred meridian effect was found because auditory and visual space were not coincident. More specifically, auditory targets would imply an unnatural "in the head" localization when delivered through headphones, which is qualitatively different from the "out there" localization of auditory targets delivered through loudspeakers. This hypothesis arises because the cognitive system did not evolve to orient to "in the head" sounds, thus a visual attention system cannot be expected to be able to deal with those sounds. If this were true, then results of previous experiments could not be interpreted as non-consistent with a visual dominance hypothesis (Ward, 1994). Indeed, previous experiments cannot rule out the hypothesis that auditory covert orienting to external sounds depends on the visual attentional system. However, the same rationale should apply the other way round. This is, as humans never encountered "in the head" sounds before the invention of headphones, only two alternatives remain: (1) Attentional orienting is not possible to sounds from inside the head (but this has been proved false); or (2) the same processes that subserve orienting of attention to sounds from the external world should also subserve orienting of attention to sounds delivered through headphones. Actually, the very same fact that our cognitive system did not evolve in order to cope with auditory stimuli from inside the head makes it very unlikely that different and separate mechanisms evolved subserving the processing of "in the head" and "out there" sounds. Indeed, to our knowledge there is no evidence in the literature that two qualitatively different mechanisms exist for localization or attention orienting to “in the head” and “out there” sounds, respectively. Thus, if one assumes that the same mechanism governs our orienting to external and internal sounds, the use of headphones should not undermine inferences about attentional processing of auditory stimuli. On the other hand, it is surely true that in our Experiments 1–5 localization of sounds was based only on intensity differences between the two ears, whereas localization of external sounds is based on multiple auditory cues. In order to clarify whether any differences exist between internal and external methods of target delivery, we ran a further experiment using the same general procedure as that in Experiment 3 with the exceptions that external loudspeakers were used to deliver auditory targets and that a discrimination task was used instead of a simple detection task.

Method

Participants

A total of 13 undergraduate volunteers took part in Experiment 6. They ranged in age from 20 to 26 years, with a mean age of 23.2 years. All participants had normal hearing and were naive as to the purpose of the study. In a preliminary test, participants were able to hear and localize correctly the auditory stimuli used throughout the experiment. None of them participated in the previous experiments.

Stimuli

Two different sounds were used as targets and distractors. The target was a natural sound produced by hitting a metallic bar on a glass. The distractor was an artificial chirped tone. Both types of stimulus had a duration of 50 ms and were synthesized at a sampling rate of 22000 Hz. They were delivered through four loudspeakers at 40 dB SPL with an 8-bit output resolution. Loudspeakers were located at 30°, 70°, 110°, and 150° relative to the head of the observer, at a distance of 50 cm. The visual cue was a graphical representation of the head and of the loudspeaker to which they should attend, displayed on a 14" computer monitor also placed at a distance of 50 cm from the observer (Figure 2). In half of the experimental blocks the visual cues were located between positions 30° and 70° to the left, in the other half they were located between locations 110° and 150° to the right. The order of the experimental blocks was randomized across participants.

Procedure

The procedure was identical to that used in Experiment 3. The only exception was the use of a discrimination task instead of a detection task. We chose a discrimination task in order to rule out the possibility that previous results depended on the specific task used. Participants had to respond as fast as possible to target sounds and withhold the respone to distractors. The experiment consisted of 604 trials. The visual cue indicated correctly the source of the incoming auditory stimulus on 80% of the trials (valid trials). The auditory stimulus was a target on 66% of the trials.

Design

Two conditions were produced by the within-subjects factor of cue validity (valid and invalid), and three conditions were produced by the within-subjects factor of meridian crossing (visual meridian crossing, head-centred meridian crossing, no crossing). Mean reaction times and proportion of

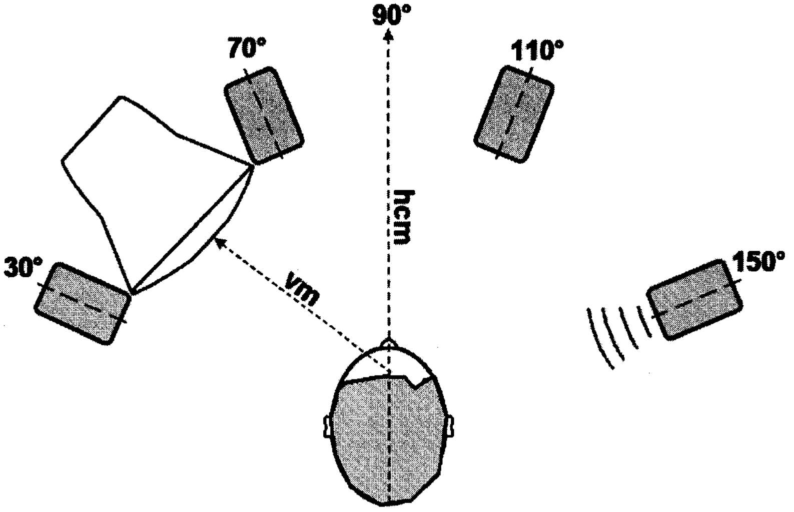

Figure 2. Relative arrangement of visual cues, locations of auditory targets, and observers' head and gaze positions in Experiment 6. The auditory targets were delivered through external loudspeakers at the depicted locations. vm: visual meridian. hcm: head-centred meridian.

errors were analysed through separate one-way ANOVAs for the cue validity and meridian-crossing factors. Mean reaction times were computed for each experimental condition after having removed trials on which a response occurred before 100 ms from tone offset or after 800 ms from tone onset. Also in Experiment 6, the equivalence of the locations of the target tones was tested through two separate ANOVAs on mean reaction times and on proportion of errors on valid trials for each spatial location.

Results and discussion

On average, RTs fell outside the acceptable range on about 9% of trials. ANOVA on the remaining RT data showed a significant main effect of validity (valid, invalid), $F(1, 12) = 22.31$, $p < .001$. The analysis of RTs to invalid trials (visual meridian, head-centred meridian, no crossing) showed a significant effect of meridian crossing, $F(2, 24) = 3.6$, $p < .05$ (Geisser–Greenhouse epsilon = .83). Duncan's test showed that RTs were significantly slower on invalid trials in which attention had to be moved across the head-centred vertical meridian than on invalid trials in which attention had to be moved across the visual meridian ($p < .05$) or without crossing any meridian ($p < .05$, Table 6). The same analysis on arcsine transformation of proportions of errors to target stimuli did not reveal any effect of the crossing condition, $F(2, 24) = 0.55$, $p = .52$. The number of distractors erroneously responded to (false alarms) was too low to allow an analysis on d' scores.

The results of Experiment 6 confirm and extend those found in the previous experiments. Indeed, the use of loudspeakers instead of headphones, and the use of natural sounds as targets instead of pure tones, did not prevent us observing a head-centred meridian effect.

TABLE 6
Mean reaction times and mean proportion of errors as a function of cue validity and meridian crossing in Experiment 6

		RT[a]		*Proportion of errors*	
Condition		*M*	*SD*	*M*	*SD*
Cue validity	Valid	253.53	74.57	.06	.06
	Invalid	276.90	71.92	.12	.21
Meridian crossing	Visual	264.68	66.33	.12	.21
	Head centred	289.57	85.69	.13	.23
	No crossing	269.41	81.87	.11	.20

[a] Reaction times, in ms.

GENERAL CONCLUSIONS

In our experiments, we addressed the issue of whether separate visual and auditory attention systems exist by looking at the meridian effect on reaction times to auditory targets. As this effect is unrelated to participants' expectancies and does not interact with the specific task they performed, converging evidence for one of the three hypotheses was expected. Indeed, our results provided converging evidence that auditory and visual spatial attention are differently organized, at least in so far as mechanisms leading to the appearance of meridian effects are concerned. It has been frequently reported that individuals show slower reaction times to visual stimuli when cued and target locations are separated by the visual vertical meridian (Hughes & Zimba, 1985, 1987; Reuter Lorenz & Fendrich, 1992; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). In our experiments participants showed a similar effect of delay in responding to auditory stimuli when cued and target locations were separated by the head-centred vertical meridian (Figure 3).

The presence of a head-centred meridian effect was found when the cue was visually presented (Experiments 2 and 3) as well as when it was auditorily presented (Experiment 5), when the cue was peripheral (and informative) as well as when it was central (Experiments 2, 3, and 5), and when the sounds were delivered through headphones as well as when they were delivered from external loudspeakers (Experiments 2, 3, 5, and 6). Furthermore, the head-centred meridian effect on RTs to auditory targets was not due to a general effect of our experimental setting or of head position, as the same procedure yielded the well known visual meridian effect on reaction times to visual targets (Experiment 4). As in the present experiments eye movements were not monitored, it is important to note that the head-centred meridian effect cannot be accounted for by overt orienting, as participants had their gaze shifted relative to their head position. Indeed, when cued and target locations were separated by the head-centred meridian, they were still on the same side of the fixation point, and any effect of eye movements should have equally affected reaction times to stimuli presented at those locations. Moreover, reaction times on no-crossing trials were faster than reaction times on head-centred meridian-crossing trials in all the experiments where a head-centred meridian effect was found. This pattern of results also rules out any eye movements

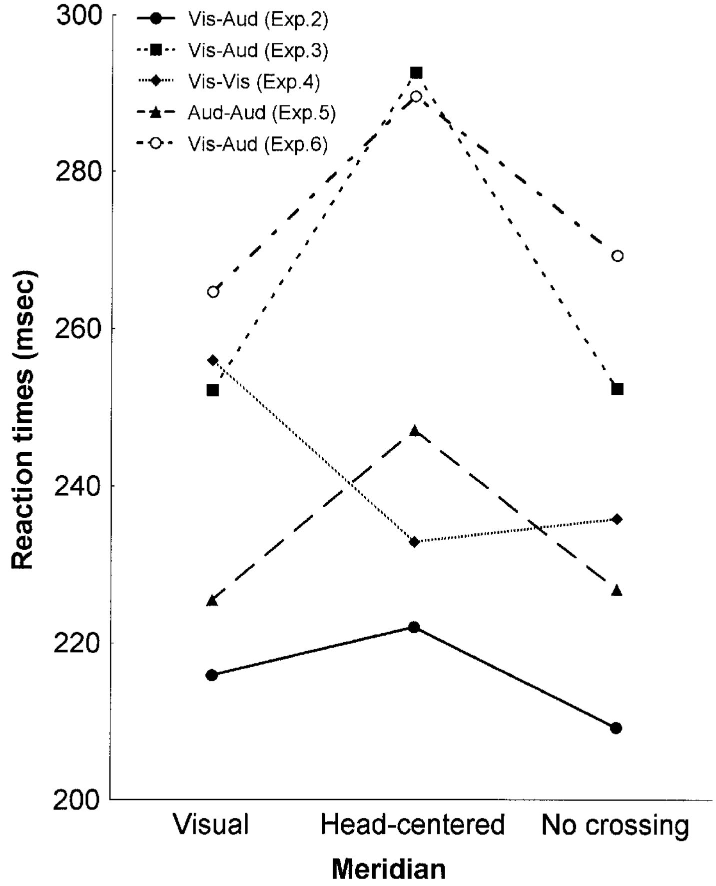

Figure 3. Mean reaction times (ms) on invalid trials in which cued and target locations were separated by the visual meridian, by the head-centred meridian, or by no meridian (no crossing), as a function of the sensory modality of cues and targets (Experiments 2–6). For graphical purposes, data from Experiment 3 have been collapsed across stimulus frequencies. Vis–Aud: visual cue, auditory target; Vis–Vis: visual cue, visual target; Aud–Aud: auditory cue, auditory target.

accounting for the meridian effect we reported, as target locations on no-crossing trials were farther from the fixation point than target locations on head-centred meridian crossing trials.

The results of these experiments bear directly on the hypotheses that have been proposed in order to account for the relationship between visual and auditory spatial attention. For instance, the clear dissociation between visual and head-centred meridian effects in vision and audition disconfirms any strong version of the supramodal hypothesis of endogenous visual and auditory spatial attention. Notwithstanding this, a supramodal attention system appears physiologically plausible, as it might depend on the activity of mulitsensory neurons that have been found in cortical and subcortical areas in primate brain (e.g., Morrel, 1972; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981) including the superior colliculus (Stein, Meredith, &

Wallace, 1993). Its engagement, however, should give rise to the same meridian effect in visual as well as in auditory attention orienting, either visual or head–centred.

Similarly, the hypothesis that visual spatial attention dominates auditory spatial attention cannot account for our results, as it would also predict that a visual meridian effect should be found when individuals are required to make a response to auditory targets. Notably, the hypothesis of the visual attention system dominance is consistent with recent neurophysiological findings that show that the receptive fields of auditory neurons in the monkey superior colliculus, which are organized within a two-dimensional spatial map, shift with the direction of gaze (Hartline, Pandey Vimal, King, Kurylo, & Northmore, 1995; Jay & Sparks, 1984, 1987; Peck, Baro, & Warder, 1995). As a result of this shift, the coordinates of the auditory spatial representation seem to be transformed into an oculocentric frame of reference, so that they may be in approximate agreement with the retinotopic coordinates of superimposed visual representations within this midbrain area. Although these findings represent a good neurophysiological basis for the visual attention dominance hypothesis, they are not in agreement with our data. Indeed, if the relationship between auditory and spatial attention was modelled upon the latter system, we would also have observed a visual meridian effect in auditory orienting.

Results of our experiments are in better agreement with the hypothesis that visual and auditory orienting are subserved by different neural systems, at least in so far as endogenous mechanisms of spatial attention are concerned. In this sense, they are compatible to the "separable-but-linked" hypothesis and represent a better specification of it, in that the "separable" part of the hypothesis might consist of the use of different spatial maps by the two attention systems, with different and specific features. This interpretation of our results might be questioned by distinguishing between attentional control mechanisms responsible for directing attention to spatial locations, and the resulting effects of attentional orienting on stimuli processing (LaBerge, 1995). Indeed, orienting of spatial attention may affect visual and auditory perceptual processing, which occur within brain in modality-specific regions, and hence findings showing an attentional modulation of modality-specific perceptual processes do not imply that the control of spatial attention is also modality specific. It should be noted, however, that our experiments were concerned with endogenous mechanisms of spatial attention, as informative cues and long stimulus-onset asynchronies were always used. This makes it unlikely that the meridian effects we observed were merely the reflections of the initial stages of visual and auditory perceptual processes.

As our results show that auditory orienting affects performance also on a non-spatial task, the problem is to explain the mechanisms that make it possible. McDonald and Ward (1999) argued that three hypotheses may be advanced with respect to this question. The first one is just based on the finding that attention orienting to a particular location affects non-spatial judgements about auditory targets and states simply that covert auditory orienting is mediated by peripheral mechanisms even though they are non-spatial in nature. Evidently, such a hypothesis sounds quite unsatisfying, as it merely describes an empirical result. The second hypothesis states that whenever a preceding sound activates location-sensitive neurons then spatial attention will influence any response to a subsequent target sound. However, this hypothesis does not seem compatible with the null effect of spatial cueing on auditory target detection reported in the literature. The third hypothesis, the one they proposed, states that activation of location-sensitive neurons is necessary but non-sufficient for covert orienting to occur. The spatial relevance hypothesis (McDonald & Ward, 1999) asserts that the spatial location of an auditory target has to be relevant to the accomplishment of the listener's task for the facilitatory and inhibitory effects of covert spatial orienting to occur in audition. Our results seem in fair agreement with this hypothesis, as asking individuals to detect an auditory target at one of four likely spatial locations strengthens the spatial component of the task more than asking them to detect an auditory target from only two possible locations.

Recently, Schmitt, Postma, and De Haan (2000) used a setting involving four spatial locations and reported very similar distance effects in both unimodal and cross-modal conditions. However, our experiments further characterize the cross-modal links between auditory and visual attention by showing that they are affected by different meridians. Our evidence could hence be the starting point for reaching a conclusive definition of the cross-modal links between subsystems underlying spatial attention.

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