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ORIGINAL PAPER

Unimodal and Crossmodal Gradients of Spatial Attention: Evidence from Event-related Potentials

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Abstract Behavioral and event-related potential (ERP) studies have shown that spatial attention is gradually distributed around the center of the attentional focus. The present study compared uni- and crossmodal gradients of spatial attention to investigate whether the orienting of auditory and visual spatial attention is based on modality specific or supramodal representations of space. Auditory and visual stimuli were presented from five speaker locations positioned in the right hemifield. Participants had to attend to the innermost or outmost right position in order to detect either visual or auditory deviant stimuli. Detection rates and event-related potentials (ERPs) indicated that spatial attention is distributed as a gradient. Unimodal spatial ERP gradients correlated with the spatial resolution of the modality. Crossmodal spatial gradients were always broader than the corresponding unimodal spatial gradients. These results suggest that both modality specific and supramodal spatial representations are activated during orienting attention in space.

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Introduction

Input from different sensory systems enhances the ability to detect relevant events in the environment. Research has shown that the spatial position encoded by every sensory system is used to link inputs across modalities (see Driver and Noesselt 2008; Spence and Driver 2004; Stein and Stanford 2008, for overviews). If input of more than one modality arises from the same location in space, this event is processed more efficiently. In humans, ERPs in response to spatially congruent and incongruent bimodal audio-visual stimuli have been found to differ starting at about 160 ms, suggesting that the spatial coordinate systems of vision and hearing have been matched at this processing stage (Gondan et al. 2005).

A large number of ERP studies have used spatial attention paradigms in order to test how spatial attention is distributed within and across modalities (see e.g., Eimer 2004). A well accepted finding is that orienting attention to a particular location in order to detect stimuli of one modality enhances the processing of stimuli in a task irrelevant modality at that location as well (Eimer 2004; Hillyard et al. 1984; Hötting et al. 2003). The latency (shorter than 200 ms) of these spatial attention ERP effects suggests that crossmodal spatial attention modulates sensory processing stages in the brain.

It has been argued that these crossmodal attention effects originate from an activation of a supramodal spatial representation that allows a matching of the spatial coordinates of different modalities (McDonald et al. 2003).

In most of these studies two locations were used, one in the left and one in the right hemifield (Eimer and Schröger 1998; Hötting et al. 2003; Teder-Sälejärvi et al. 1999). Although these studies suggest that spatial attention is crossmodally oriented within one hemifield, it is not possible to conclude whether or not attention is allocated based on a common supramodal representation of space: This would require demonstrating that the distribution of spatial attention effects is the same for a primary and secondary modality. To approach this question, Eimer et al. (2004) conducted an ERP experiment in which they used four locations, two in each hemifield. They showed that crossmodal attention effects (using visual and auditory stimulation) were not uniformly distributed within a hemifield but depend on the attentional focus of the primary modality within a hemifield (see Eimer and Van Velzen 2005, for similar findings in touch and vision).

Although these studies suggest that a possible supramodal spatial representation has a resolution higher than the level of a hemifield, the use of only two locations with a spatial separation of about 30 degrees (and therefore far above the spatial resolution of both the visual and auditory modality) does not allow deciding whether or not identical spatial representations are used for unimodal and crossmodal spatial attention shifts. In the present study five locations on the right side of the fixation point were used instead of only two locations within each hemifield.

Results from behavioral, ERP and fMRI studies suggest that spatial attention is distributed like a gradient for the auditory (e.g., Teder-Sälejärvi et al. 1999), visual (e.g., Downing and Pinker 1985; Mangun and Hillyard 1988; Müller et al. 2003) and tactile modality (Schicke and Röder 2008); that is, spatial attention seems to enhance stimulus processing at one location most and to a lesser degree at adjacent locations. The width of this gradient seems to depend on the spatial resolution of a modality and on the processing level (Teder-Sälejärvi et al. 1999). For example, it has been shown that the auditory spatial attention gradient is steeper in the centre (around zero degree azimuth) than in the periphery (at 90 degree azimuth) corresponding to the higher spatial resolution of the auditory system for central sound sources (Röder et al. 1999; Teder-Sälejärvi et al. 1999). Moreover, broader attention gradients were observed for early than for later ERPs (Teder-Sälejärvi et al. 1999) suggesting that attentional selection is continuously narrowed down.

The present study measured ERP attentional gradients to auditory and visual stimuli in order to compare attentional gradients for different modalities and for attentional orienting within and across modalities. In contrast to Eimer et al. (2004), we used a within participant design in which participants had to attend either to visual or to auditory stimuli which were presented from five different locations within the right hemifield. In half of the blocks participants had to detect deviants from the innermost (central) location, in the other half of the blocks they had to detect deviants from the rightmost (peripheral) location. Spatial attention effects (attention to the central location vs. attention to the peripheral location) were analyzed for each speaker (1–4) and separately for the Attend Vision and the Attend Audition condition. Gradients of spatial attention were assessed comparing ERPs to stimuli presented at the four speaker locations (6°, 12°, 18°, 24°) when the central speaker (6°) was attended with ERPs to the same stimuli when the peripheral speaker (80°) was attended. We expected that spatial ERP attention effects progressively decline with increasing distance from the central speaker position. Due to the higher spatial resolution of the visual system, steeper attention gradients were expected for visual than for auditory stimuli (unimodal attention gradients).

If crossmodal spatial attention effects are mediated by a common supramodal spatial representation, the gradients of crossmodal spatial attention effects are expected to be similar for auditory and visual task irrelevant stimuli and not more precisely tuned than the worst tuned sensory modality. If uni- and crossmodal spatial attention effects emerge from the same spatial representation, uni- and crossmodal spatial attention gradients are expected to be indistinguishable.

Methods

Participants

Fifteen volunteers participated in the experiment. They received either course credits or were paid for participation. One participant had to be excluded from the data analysis because of excessive ocular and muscle artifacts in the electroencephalographic (EEG) recordings. The remaining participants (seven females, age: 20–34 years, mean: 24 years) had normal or corrected-to-normal vision, normal hearing and had not reported any neurological disorders. The experiment was performed in accordance with the ethical standards laid down in the Declaration of Helsinki (2000).

Materials

Auditory stimuli were bursts of white noise (68 dBA) presented from five speaker positions at a distance of 2 m from a chin rest. A fixation spot was presented straight ahead of the participant. The speakers were arranged in a quarter circle to the right of fixation, at 6° (speaker 1), 12° (speaker 2), 18° (speaker 3), 24° (speaker 4), and 80° (speaker 5) azimuth (Fig. 1a).

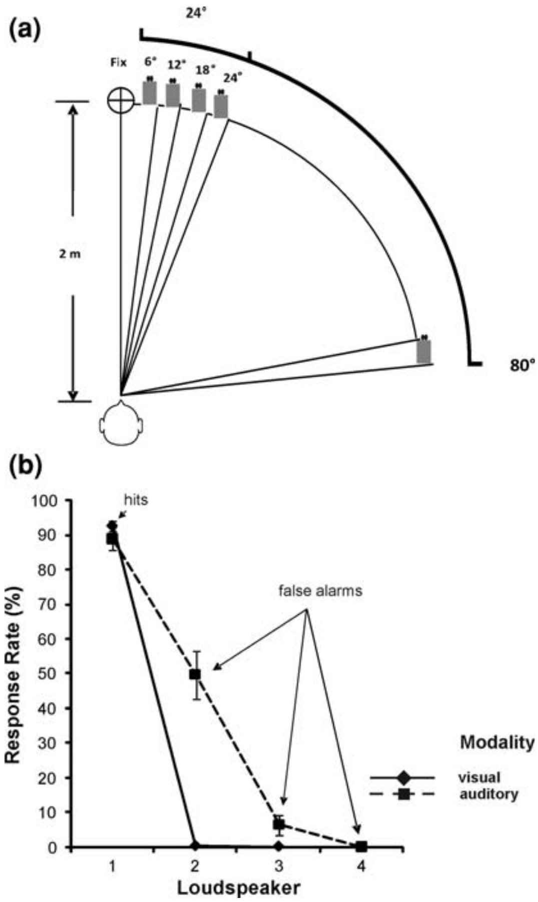

Fig. 1 Speaker layout and response gradients. **a** Schematic drawing of the arrangement of the speakers and the LEDs. **b** Response rate to the attended central speaker (hit rates) and to deviant stimuli at the adjacent speaker (false alarms) with standard error of the mean

Auditory standard stimuli ($P = .80$) had a duration of 20 ms. Deviants ($P = .20$) were two bursts of 20 ms, separated by a silent gap of 120 ms. A LED flash of 20 ms duration was used as the visual standard. Visual deviants were double LED flashes separated by 120 ms. The LEDs were mounted onto the housings of the speaker (two LEDs per speaker).

Procedure

The experiment took place in an electrically shielded, dimly lit and sound attenuating room. Participants sat at a table with their head immobilized with a chin rest. They were fixating a cross (diameter = 5 cm, covering a visual angle of $2.5° \times 2.5°$) throughout a run. Auditory and visual stimuli were presented with equal probability and in a random sequence from the five speaker positions. The interstimulus interval was varied randomly between 900 and 1100 ms.

Participants' task was either to attend to the central speaker (1) or to the peripheral speaker (5) and to respond as fast and as accurately as possible by release of a foot pedal to infrequent double noise bursts ("Attend audition") or double light flashes ("Attend vision") at the attended location, while ignoring all the other stimuli (Fig. 1a).

The experiment consisted of 16 blocks (four blocks for each condition): (1) attend audition central; (2) attend audition peripheral; (3) attend vision central; (4) attend vision peripheral yielding a total number of 1,600 standard stimuli and 400 deviant stimuli for each of the four experimental conditions. One practice block for each of the four conditions was run in order to familiarize participants with the experimental task. The location and the stimulus modality which had to be attended were changed every second block. The order of experimental conditions was counterbalanced across participants.

EEG Recording

Event-related potentials were recorded from 61 scalp electrodes mounted in an elastic cap (Easy Cap; FMS, Herrsching-Breitbrunn, Germany) at equal distance. If possible, corresponding electrode names of the 10–20 system are given in Fig. 2. Recordings were referenced to the right mastoid. Offline, an averaged right/left mastoid reference was calculated using the left mastoid recording. To monitor horizontal eye movements, two electrodes were placed at the outer canthi of each eye (bipolar recording). Vertical eye movements were monitored with an electrode below the left eye against the reference. To keep electrode impedance below 5 kΩ for scalp recordings and below 10 kΩ for eye recordings we prepared the skin with an abrasive gel (Every, Gelimed, Negernbötel, Germany) and isopropanol. Electrolyte gel was used to attain conductivity between the skin and the electrodes (Eci Electrogel; Electrocap International, Eaton, OH, USA). Recordings were amplified (Synamps amplifiers; Neuroscan, Sipplingen, Germany) with a bandpass of 0.1–40 Hz. The sample rate was set to 500 Hz.

Data Analyses

Reaction times to hit responses and response rates to deviants were calculated for each speaker separately for each of the four conditions. A button press between 100 and 1000 ms after a deviant of the task-relevant modality at the attended speaker was classified as a hit. False alarms were defined as responses after deviants at any of the other speakers. In the following, we refer to hit rates and false alarm rates as response rates; thus they were calculated as the number of responses to deviants divided by the total number of deviants at a given speaker. Analyses of variance (ANOVAs) models are specified in the result section.

Auditory and visual ERPs to standard stimuli were averaged separately for each participant, speaker (1–4), attended modality (auditory vs. visual) and attended

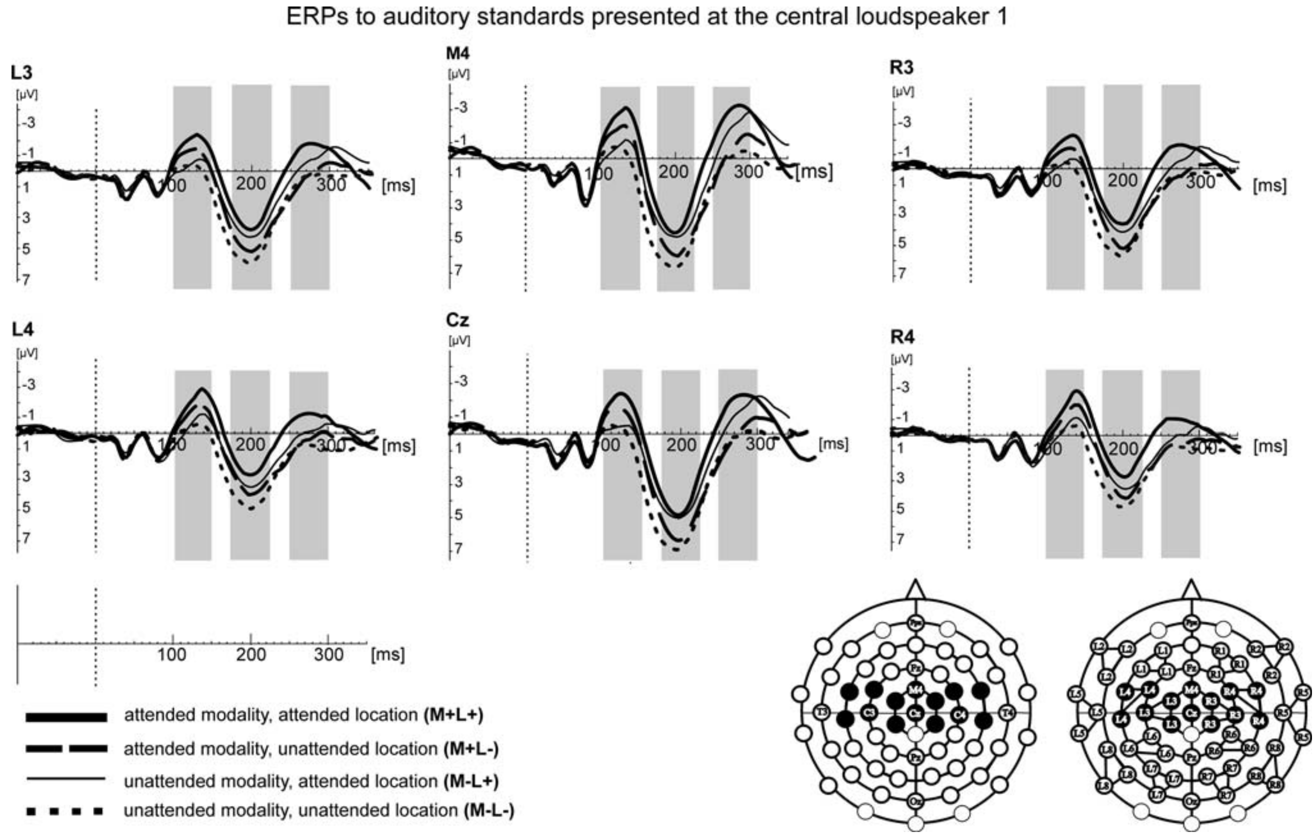

Fig. 2 Grand average ERPs to auditory standard stimuli under four different attention conditions at central left and right electrode clusters as well as for two midline electrodes (M4, Cz) (see electrode montage). Time windows used for the statistical analyses are shaded in *grey*. Negativity is plotted upwards. The electrode montage on the right shows the clustering of electrodes and cluster labels. The montage on the left gives corresponding electrode names of the 10–20 system

location (central vs. peripheral). Segments with eye movement artifacts (difference of more than 100 µV between any two values in a segment of the horizontal or vertical EOG channels) were removed. To increase the signal-to-noise ratio, three adjacent electrodes were clustered as shown in Figs 2 and 3. The average ERP of the three electrodes was calculated. The electrodes of one hemisphere were arranged into 8 clusters (L = left and R = right); the numbers 1–8 indicate the anterior–posterior dimension.

For statistical analyses mean amplitudes were calculated with respect to a 100 ms prestimulus baseline for the following time windows: auditory ERPs: 100–150 ms, 175–225 ms, 250–300 ms; visual ERPs: 150–200 ms and 225–275 ms. Results of the overall ANOVA with factors Attended Modality (*unimodal vs. crossmodal*), Attended Speaker (*attend central speaker vs. attend peripheral speaker*), Hemisphere (*right vs. left*) and Cluster (*1–8*) are reported in Tables 1 and 3.

The Huynh and Feldt correction for violations of the sphericity assumption was employed (Huynh and Feldt 1976); corrected *P*-values are reported in the result section.

In order to assess the predicted ERP gradient of spatial attention, we calculated difference potentials (attend central speaker–attend peripheral speaker) for each speaker and for the unimodal and crossmodal conditions. Thus, ERPs to auditory and visual standards at speaker 1–4 were separately subtracted when speaker 5 was attended from ERPs to the same stimuli when the central speaker 1 was task relevant. Since the amplitude of auditory potentials is maximal over fronto-central electrode positions, we analyzed the spatial gradient of attention for auditory ERPs at the central electrode M4 positioned between Fz and Cz of the international 10–20 system (for a similar analyzing strategy see Pauli and Röder 2008). Spatial gradients of attention for visual ERPs were analyzed at the occipital cluster L8 since visual attention effects were largest over the posterior scalp contralateral to stimulus presentation.

Results

Behavioral Data

An overall ANOVA for hit rates with the factors Attended Speaker (*central vs. peripheral*) and Stimulus Modality

Fig. 3 Grand average ERPs to visual standard stimuli under four different conditions at frontal, lateral and occipital recording sites (see electrode montage). Time windows used for the statistical analyses are shaded in grey. Negativity is plotted upwards

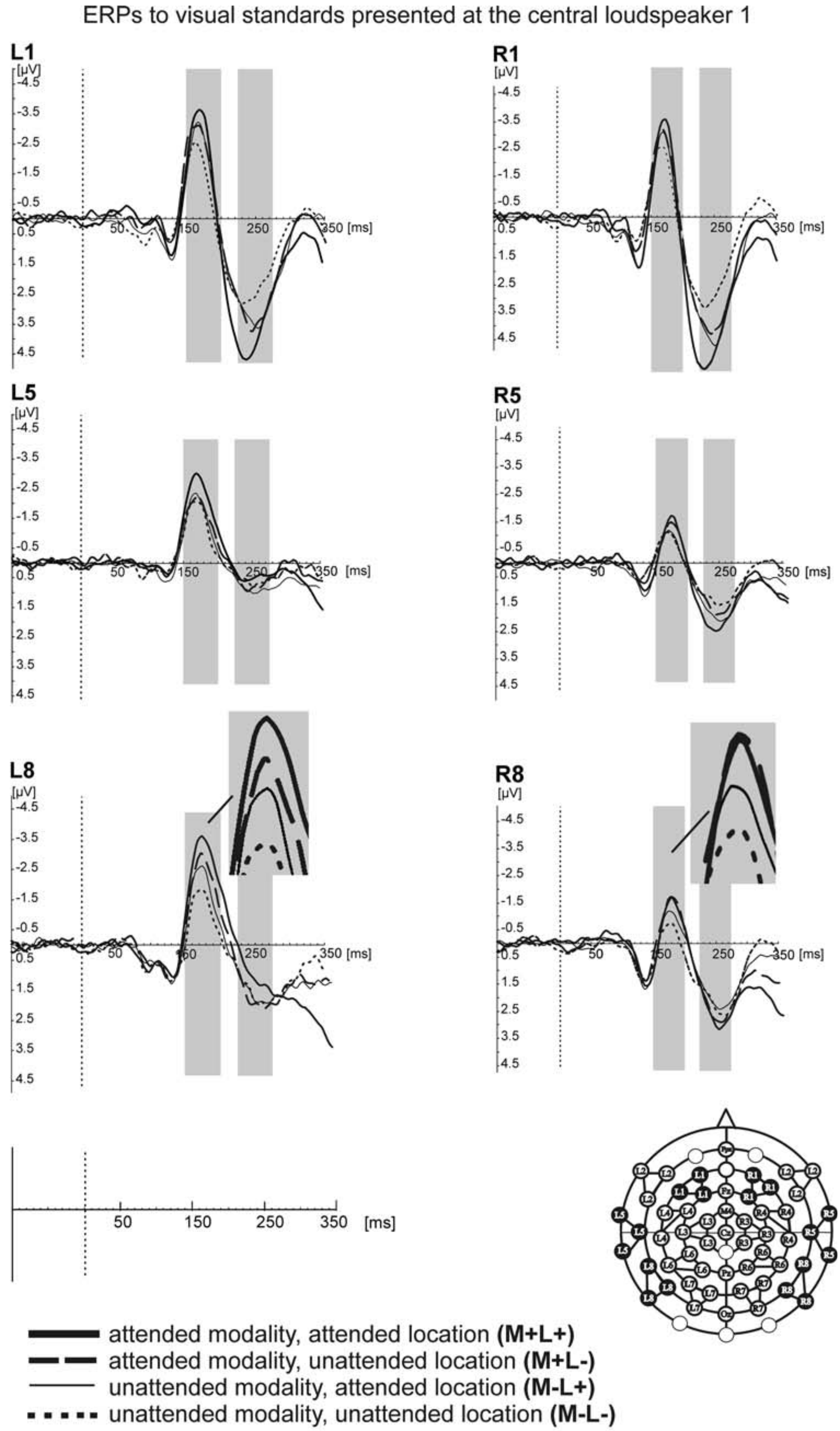

Table 1 Auditory ERPs

Factors	Time epoch		
	100–150 ms	175–225 ms	250–300 ms
(a) Overall ANOVA			
Attended Modality*Hemisphere*Cluster	3.39 ($P = 0.025$)		
Attended Modality*Cluster	11.77 ($P = 0.001$)	4.39 ($P = 0.015$)	6.94 ($P = 0.004$)
Attended Speaker*Cluster	3.15 ($P = 0.038$)	10.95 ($P < 0.001$)	13.67 ($P < 0.001$)
Attended Speaker		19.14 ($P = 0.001$)	19.72 ($P = 0.001$)
Attended Modality	53.39 ($P < 0.001$)	7.51 ($P = 0.017$)	
(b1) Separate ANOVA Attend Audition (unimodal)			
Attended Speaker*Cluster	3.44 ($P = 0.03$)	6.83 ($P = 0.001$)	6.61 ($P = 0.001$)
Attended Speaker		6.80 ($P = 0.022$)	16.36 ($P = 0.001$)
(b2) Separate ANOVA Attend Vision (crossmodal)			
Attended Speaker*Cluster	0.50 ($P = 0.621$)	6.08 ($P = 0.011$)	9.18 ($P < 0.001$)
Attended Speaker		14.56 ($P = 0.002$)	4.87 ($P = 0.046$)

(c) Factors	Electrodes	Time epoch		
		100–150 ms	175–225 ms	250–300 ms
Attended Modality	M4	52.73 ($P < 0.001$)	4.12 ($P = 0.064$)	
	Cz	50.65 ($P < 0.001$)		
Attended Speaker	M4	3.61 ($P = 0.080$)	17.71 ($P = 0.001$)	33.53 ($P < 0.001$)
	Cz	3.84 ($P = 0.072$)	20.22 ($P = 0.001$)	29.52 ($P < 0.001$)
Attended Speaker*	M4	1.94 ($P = 0.187$)	0.33 ($P = 0.576$)	0.84 ($P = 0.376$)
Attended Modality	Cz	1.46 ($P = 0.249$)	0.18 ($P = 0.682$)	0.76 ($P = 0.398$)

Results of (a) the overall ANOVA including the factors Attended Modality (unimodal vs. crossmodal), Attended Speaker (attend central speaker vs. attend peripheral speaker), Hemisphere (left vs. right) and Cluster (1–8); (b1) and (b2) separate ANOVAs for Attend Audition (unimodal condition) and Attend Vision (crossmodal condition), respectively; (c) ANOVA including the factors Attended Speaker and Attended Modality at midline electrodes M4 and Cz. Results are depicted separately for three time epochs

(*auditory vs. visual*) revealed an Attended Speaker by Stimulus Modality interaction ($F(1,13) = 7.59, P = 0.016$). Hit rates were lower for visual targets than for auditory targets at the peripheral speaker (visual peripheral: mean = 80.3%, $SE = 2.5$, auditory peripheral: mean = 90.7%, $SE = 3.9$; $P = 0.018$), but did not significantly differ at the central speaker (visual central: mean = 92.5%, $SE = 1.4$, auditory central: mean = 88.8%, $SE = 3.2$; $P = 0.262$).

As seen in Fig. 1b, the slope of the response-rate gradients differed between modalities: In the auditory modality, false alarms gradually declined with increasing distance of the task relevant location. By contrast, in the visual condition, there were hardly any false alarms at the adjacent speaker (Speaker * Stimulus Modality, $F(3,39) = 46.42$, $P < 0.001$).

T-tests calculated to further analyze the main Speaker effect for the auditory condition ($F(3,39) = 138.14$, $P < 0.001$) revealed that response rates to auditory deviants differed between each of the four speakers ($P < 0.05$). In the visual modality (main effect Speaker, $F(3,39) = 4086.39$, $P < 0.001$), response rates to deviants at speaker 1 were significantly higher than at any other speaker (all $P < 0.001$).

Response rates to standards were below 3% and did neither vary as a function of speaker nor as a function of modality.

Reaction times to central auditory stimuli (627 ms, $SE = 18$) were longer than to central visual deviants (mean = 596 ms, $SE = 12$; post hoc *t*-test $P = 0.017$); by contrast reaction times to peripheral targets did not differ between modalities (Attended Speaker * Stimulus Modality, $F(1,13) = 8.94$, $P = 0.01$).v

Event-related Brain Potentials

Auditory ERPs to Stimuli from the Central Speaker Position 1

As seen in Fig. 2, ERPs to auditory stimuli presented at the central speaker position started to differ as a function of spatial attention at about 100 ms after stimulus onset

Table 2 Statistical results for single clusters

	Time epoch		
	100–150 ms	175–225 ms	250–300 ms
Unimodal	L3, L4	L3, L4, L6	L1, L2, L3, L4, L6, L7, L8
	R3, R4	R3, R4, R5, R6, R8	R1, R3, R4, R5, R6, R7, R8
	M4, Cz	M4, Cz	M4, Cz
Crossmodal		L1, L2, L3, L4, L5, L6, L7, L8	L1, L2, L3, L4
		R1, R3, R4, R6, R7	R1, R2, R3, R4
		M4, Cz	M4, Cz

Clusters with significant differences (*t*-tests with $P < 0.05$) between ERPs to attended as compared to unattended auditory stimuli are listed. *L* left hemisphere; *R* right hemisphere, *M* midline electrodes. The numbers indicate the position of the electrodes along the anterior–posterior dimension (see Fig. 2)

(spatial attention effect). ERP spatial attention effects were observed when auditory stimuli were task relevant (unimodal spatial attention effect) starting at about 100 ms and when auditory stimuli were task irrelevant (crossmodal spatial attention effect) starting at about 150 ms.[1] For auditory ERPs, spatial attention effects were maximal over central clusters 3 and 4. Therefore, results were presented for these clusters as follows. Detailed results of the overall ANOVA including all electrode clusters are reported in Table 1 and follow-up *t*-tests in Table 2.

Time Epoch 100–150 ms ANOVAs for single central clusters including the factors Attended Modality (*unimodal vs. crossmodal*) and Attended Speaker (*attend central speaker vs. attend peripheral speaker*) revealed a marginal significant main effect of Attended Speaker bilaterally at cluster 3 ($F(1,13) > 3.38$, $P < 0.09$). The interaction between the factors Attended Modality and Attended Speaker was marginally significant at cluster R4 ($F(1,13) = 4.5$, $P = 0.054$).

T-tests separately calculated for the *unimodal* and *crossmodal conditions* revealed reliable differences between ERPs to stimuli at the attended position as compared to the unattended location only when audition was task relevant ($P < 0.05$ for clusters R3, L3, R4, L4).

Time Epoch 175–225 ms ERPs between 175 and 225 ms to auditory stimuli at the central speaker were enhanced by spatial attention both in the Attend Vision and Attend Audition condition.

Separate ANOVAs run at each central cluster revealed a main effect of Attended Speaker ($F(1,13) > 16.77$, $P < 0.01$) bilaterally at central clusters 3 and 4.

Post hoc *t*-tests calculated for each cluster separately for the *unimodal* and *crossmodal conditions*, confirmed a significantly enhanced negativity for stimuli at the attended location in both conditions bilaterally at central clusters 3 and 4 ($P < 0.05$).

Time Epoch 250–300 ms ERP spatial attention effects were significant for both, the Attend Vision and Attend Audition conditions. A significant main effect of Attended Speaker was observed bilaterally for central clusters 3 and 4 ($F(1,13) > 23.14$, $P < 0.001$). Moreover, the interaction between Attended Modality and Attended Speaker was marginal significant at cluster R4 ($F(1,13) = 3.35$, $P = 0.090$).

Separate analyses for single clusters for the *unimodal* and *crossmodal conditions* confirmed a significantly enhanced negativity for stimuli of the attended compared to the unattended location for both conditions bilaterally at central clusters 3 and 4 ($P < 0.05$).

Visual ERPs to Stimuli from the Central Speaker Position 1

ERPs to visual stimuli presented at the central location started to differ at about 150 ms after stimulus onset as a function of spatial attention and intermodal attention (Fig. 3). The onset of the spatial attention effect for visual ERPs was similar for the Attend Vision and Attend Audition condition. For visual ERPs, spatial attention effects were maximal over occipital clusters 8 and lateral clusters 5. Therefore, statistical results were presented for these clusters in the following. Results of the overall ANOVA including all electrode clusters are reported in Table 3 and *t*-tests for single clusters in Table 4.

Time Epoch 150–200 ms The ANOVA revealed a main effect of Attended Speaker at occipital cluster L8 and at lateral cluster L5 ($F(1,13) > 11.69$, $P < 0.05$).

A significant interaction between the factors Attended Modality and Attended Speaker was observed at cluster R8 ($F(1,13) = 7.96$, $P = 0.014$). This effect was marginal significant at cluster L5 ($F(1,13) = 3.19$, $P = 0.097$).

[1] Intermodal attention effects consisting of larger amplitudes of ERPs to stimuli when their modality was attended compared to when their modality was unattended were observed in the present experiment for auditory and visual stimuli (see Figs. 2, 3); we report the significant Attended Modality effects of the overall ANOVAs in Tables 1 and 3 but, due to space limitations, we do not discuss them in detail. Nevertheless, intermodal attention effects confirm that participants were indeed selectively attending one modality only.

ERP effects of spatial and intermodal attention were significant at the peripheral speaker as well. Since the main focus of the present study was on attention gradients, we do not report ERPs to peripheral stimuli in the present paper.

Table 3 Visual ERPs

Factors	Time epoch	
	150–200 ms	225–275 ms
(a) Overall ANOVA		
Attended Modality*Attended Speaker*Hemisphere*Cluster		4.49 ($P = 0.003$)
Attended Modality*Attended Speaker*Hemisphere		4.63 ($P = 0.051$)
Attended Modality*Attended Speaker *Cluster		6.08 ($P = 0.003$)
Attended Modality*Hemisphere*Cluster	2.06 ($P = 0.093$)	2.15 ($P = 0.088$)
Attended Modality*Cluster	5.37 ($P = 0.011$)	3.46 ($P = 0.044$)
Attended Modality*Hemisphere	5.11 ($P = 0.042$)	
Attended Speaker*Cluster		9.34 ($P < 0.001$)
Attended Speaker*Hemisphere*Cluster		2.49 ($P = 0.067$)
Attended Speaker*Hemisphere	13.64 ($P = 0.003$)	9.30 ($P = 0.009$)
Attended Speaker		15.07 ($P = 0.002$)
Attended Modality	9.30 ($P = 0.009$)	
(b1) Separate ANOVA Attend Vision (unimodal)		
Attended Speaker*Hemisphere	11.17 ($P = 0.005$)	14.41 ($P = 0.002$)
Attended Speaker*Cluster		7.01 ($P = 0.001$)
(b2) Separate ANOVA Attend Audition (crossmodal)		
Attended Speaker*Hemisphere*Cluster		5.65 ($P = 0.001$)
Attended Speaker*Cluster	3.48 ($P = 0.085$)	8.19 ($P < 0.001$)
Attended Speaker		11.86 ($P = 0.004$)

Results of a) the overall ANOVA including the factors Attended Modality (unimodal vs. crossmodal), Attended Speaker (attend central speaker vs. attend peripheral speaker), Hemisphere (left vs. right) and Cluster (1–8); b1) and b2) separate ANOVAs for Attend Vision (unimodal condition) and Attend Audition (crossmodal condition), respectively. Results are depicted separately for two time epochs

Table 4 Statistical results for single clusters

	Time epoch	
	150–200 ms	225–275 ms
Unimodal	L5, L8	L2, L8
		R2, R5, R7
Crossmodal	L8	L1, L3, L4, L6
	R8	R1, R2, R3, R4, R5, R6

Clusters with significant differences (t-tests with $P < 0.05$) between ERPs to attended as compared to unattended visual stimuli are listed. *L* left hemisphere, *R* right hemisphere, *M* midline electrodes. The numbers indicate the position of the electrodes along the anterior–posterior dimension (see Fig. 3)

Separate analyses for single clusters confirmed significant spatial attention effects over the left (contralateral) hemisphere at clusters L8 and L5 in the *unimodal condition* (occipital and lateral clusters, $P < 0.05$) and over occipital cortex bilaterally (L8, R8) in the *crossmodal condition* ($P < 0.05$).

Time Epoch 225–275 ms ERPs to stimuli presented at the central speaker position were more positive when the central speaker was attended compared to when unattended, both in the unimodal and the crossmodal condition. At contralateral occipital sides (cluster L8), however, an enhanced negativity was seen when stimulus position was attended as compared to the unattended condition.

The ANOVA revealed a significant main effect of Attended Speaker at cluster R5 ($F(1,13) = 20.58$, $P = 0.001$) and a marginal significant effect at cluster L8 ($F(1,13) = 3.99$, $P = 0.067$).

A marginal significant interaction between the factors Attended Modality and Attended Speaker ($F(1,13) = 3.23$, $P = 0.095$) was observed at cluster L8.

Post hoc t-tests revealed a significantly enhanced positivity for the attended location compared to the unattended location for the unimodal and crossmodal conditions at lateral cluster R5. An enhanced negativity to the attended compared to the unattended location was observed at the occipital cluster L8 for the unimodal condition, ($P < 0.05$).

Gradients of Spatial Attention

Auditory Gradient of Spatial Attention

ERPs to auditory stimuli presented at the central speaker array when the peripheral speaker was attended were subtracted from ERPs to the same stimuli when the central speaker was attended. These difference ERPs were calculated for each speaker both for the uni- and crossmodal conditions. We asked whether there was a decline of ERP spatial attention effects with increasing distance from the attended speaker and whether such a gradient differed between the unimodal and crossmodal conditions. Since

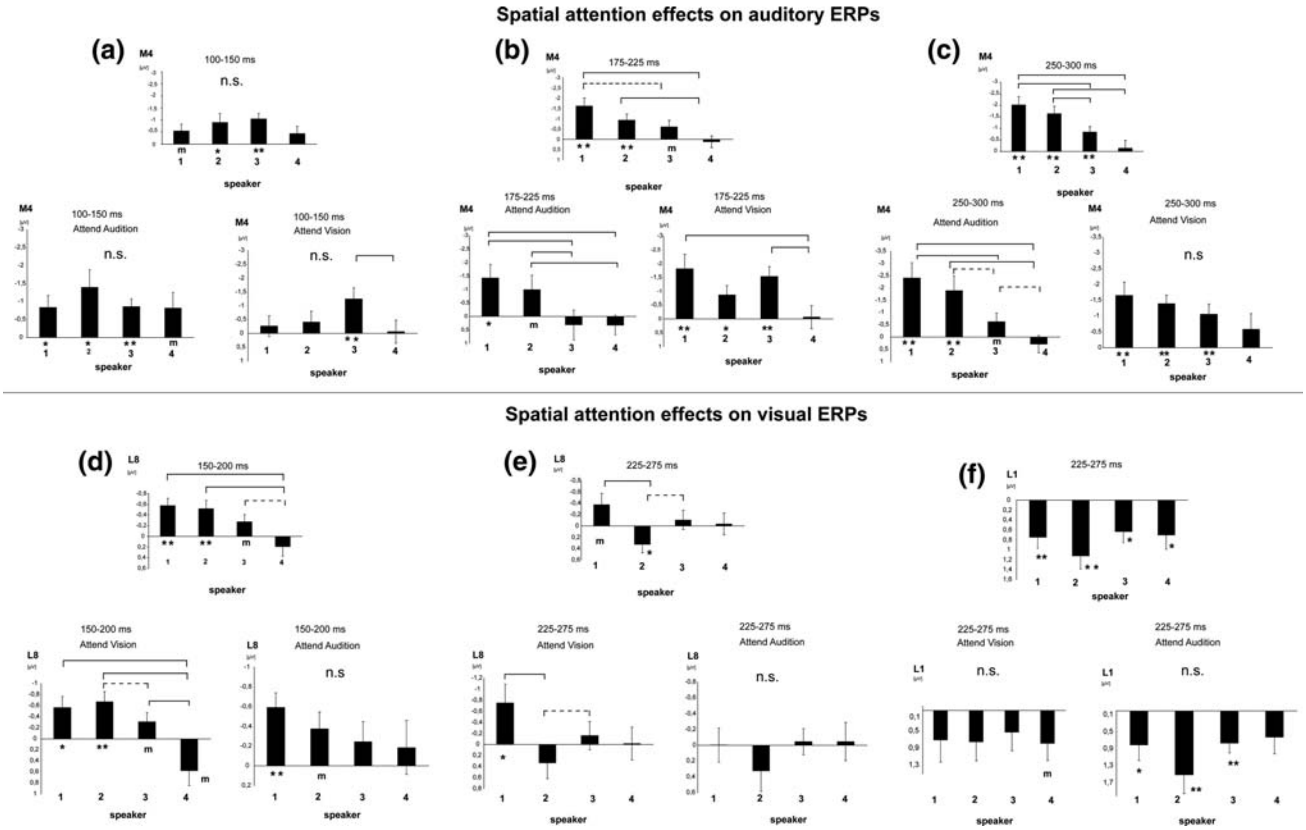

Fig. 4 Mean difference amplitudes (ERPs to stimuli at the attended position minus ERPs to stimuli at the unattended position) for the auditory ERPs for time epochs 100–150 ms, 175–225 ms and 250–300 ms at electrode M4, and for the visual ERPs for time epoch 150–200 ms at cluster L8 and 225–275 ms at cluster L8 and L1. Significant differences between speakers are marked with solid lines ($P < 0.05$), marginal significant differences with *dashed lines* ($P < 0.10$). Attention effects which deviated significantly from test value zero are marked with stars (** $P < 0.01$; * $P < 0.05$; m = $P < 0.10$; n.s. = $P > 0.10$). Error bars indicate the standard error of the mean

spatial attention effects on auditory ERPs were maximal over central midline electrodes, we analyzed gradients of spatial attention at electrode M4.

Time Epoch 100–150 ms Despite significant spatial attention effects, a gradual decline of the size of this effect across speakers was not observed (see Fig. 4a).

The ANOVA comprising the factors Attended Modality (*unimodal vs. crossmodal*) and Speaker (*1–4*) showed a marginal significant Attended Modality by Speaker interaction ($F(3,39) = 2.38$, $P = 0.084$). Spatial attention effects were significant or at least marginally significant different from zero at speakers 1, 2 and 3 (see Fig. 4a, upper line for P-values). However, there were no significant differences in the amplitude of the attention effects between speakers.

A similar pattern of results emerged when the data of the Attend Audition (unimodal) condition was separately analyzed (see Fig. 4a bottom). In the Attend Vision (crossmodal) condition, reliable spatial attention effects were observed for speaker 3 only. Separate ANOVAs for the *unimodal* and *crossmodal conditions*, however, revealed no significant Speaker effect ($P > 0.1$).

These results suggest a broadly distribution of spatial attention in the auditory modality in this time window.

Time Epoch 175–225 ms The negative spatial attention effect was largest for speaker 1 and declined in amplitude with increasing distance from the central speaker 1 (see Fig. 4b).

The overall ANOVA for ERPs at M4 including the factors Attended Modality (*unimodal vs. crossmodal*) and Speaker (*1–4*) revealed a main effect of Speaker ($F(3,39) = 4.93$, $P = 0.005$) and a marginal significant interaction of Attended Modality and Speaker ($F(3,39) = 2.59$, $P = 0.072$). Post hoc comparisons of the amplitude of the spatial attention effects at the four speakers confirmed a significant difference between speaker 1 and 4 and between speaker 2 and 4 (see Fig. 4b, upper line). A marginal significant difference was observed between speaker 1 and 3. Attention effects differed significantly from zero at speaker 1 and speaker 2 and marginally significantly at speaker 3. Separate ANOVAs for the *unimodal* and *crossmodal conditions* revealed a main effect of Speaker for both the unimodal and the crossmodal condition (unimodal: $F(3,39) = 4.18$, $P = 0.012$; crossmodal condition: $F(3,39) = 3.78$, $P = 0.018$) suggesting a gradual decline of spatial attention effects in both conditions. ERP attention gradients were steeper in the uni- than in the crossmodal condition: Post hoc comparisons with *t*-tests showed that speakers 1 and 2 differed significantly from both speakers 3 and 4 in the unimodal condition (Fig. 4b, lower line). Moreover, spatial attention effects differed significantly or at least marginally significantly from zero only at speakers 1 and 2. In the crossmodal condition, no difference in the amplitude of the spatial attention effects was seen between speakers 1, 2 and 3. However, spatial attention effects were reliable for the first three speakers (Fig. 4b, lower line). Only crossmodal spatial attention effects at speaker 4 differed significantly from effects at the first and the third speaker. The results suggest a broader tuning of spatial attention effects in the crossmodal than in the unimodal condition.

Time Epoch 250–300 ms

There was a gradual decline of the spatial attention effect across speakers (see Fig. 4c).

The overall ANOVA including the factors Speaker and Attended Modality revealed a main effect of Speaker ($F(3,39) = 8.48$, $P < 0.001$). Post hoc *t*-tests confirmed significantly larger spatial attention effects at speakers 1 and 2 as compared to speakers 3 and 4 with spatial attention effects differing from zero at the first three speakers (see Fig. 4c, upper line). Separate ANOVAs for the *unimodal* and the *crossmodal condition* were calculated. They revealed a main effect of Speaker for the unimodal condition only ($F(3,39) = 6.75$, $P = 0.003$); crossmodal condition: $F(3,39) = 1.42$, $P = 0.258$).[2]

Post hoc *t*-tests for the Attend Audition condition confirmed significantly or at least marginally significantly larger spatial attention effects at speakers 1 and 2 as compared to speakers 3 and 4 and a marginally significant difference between speaker 3 and 4. Significant spatial attention effects were observed for the first two speakers and marginal for the third speaker. The Speaker effect was not significant in the crossmodal condition (the Attend Vision condition, Fig. 4c, lower line).

Thus, although a gradient of spatial attention was seen in the unimodal condition in this time epoch, hardly any decline of the reliable spatial attention effects was seen in the crossmodal condition.

Visual Gradients of Spatial Attention

Time Epoch 150–200 ms As effects of spatial attention on visual ERPs were maximal over contralateral occipital areas, gradients of spatial attention were analyzed for cluster L8. ERP attention effects at the first three speaker locations were larger than those at speaker 4 (see Fig. 4d).

The ANOVA including the factors Attended Modality and Speaker revealed a main effect of Speaker at cluster L8 ($F(3,39) = 6.23$, $P = 0.002$). Spatial attention effects differed significantly from zero at speakers 1 and 2 and marginal at speaker 3 (see Fig. 4d, upper line). A similar pattern of results emerged when analyzing the data of the Attend Vision (unimodal) condition. Separate ANOVAs for the *unimodal* and *crossmodal conditions* were calculated. They revealed a main effect of Speaker for the unimodal condition ($F(3,39) = 7.37$, $P = 0.001$) but not for the crossmodal condition ($F(3,39) = 0.75$, $P = 0.52$).[3]

Post hoc *t*-tests showed larger spatial attention effects for speakers 1, 2 and 3 as compared to speaker 4 for the unimodal condition (see Fig. 4d, lower line). Furthermore, there was a marginal significant difference between attention effects at speakers 2 and 3. Negative spatial attention effects differed significantly from zero at speakers 1 and 2 and marginally from zero at speaker 3.

No differences between speakers were observed when comparing spatial attention effects in the crossmodal condition suggesting that there was no reliable gradient of visual spatial attention effects when audition was attended.

Time Epoch 225–275 ms In this time window, an enhanced negativity to spatially attended stimuli was seen for speaker position 1 only (see Fig. 4e): The ANOVA including the factors Modality and Speaker revealed a significant main effect of Speaker ($F(3,39) = 3.15$, $P = 0.036$). Post hoc *t*-tests obtained significant differences between speakers 1 and 2 and a marginal significant effect between speakers 2 and 3. Attention effects differed significantly from zero at speaker 2 and marginal at speaker 1 (see Fig. 4e, upper line).

[2] From Fig. 4c, the impression might emerge that the amplitude of the spatial attention effect decreases linearly across speakers both in the unimodal and crossmodal condition. We explicitly tested for a linear trend by fitting linear regression lines for each participant. While the linear trend was significant in the unimodal condition ($t(13) = 3.23$, $P = 0.007$), it failed to reach significance level in the crossmodal condition ($t(13) = 1.36$, $P = 0.198$).

[3] From Fig. 4d, the impression might emerge that the amplitude of the spatial attention effect decreases linearly across speakers both in the unimodal and crossmodal condition. We explicitly tested for a linear trend by fitting linear regression lines for each participant. While the linear trend was significant in the unimodal condition ($t(13) = 3.64$, $P = 0.003$), it failed to reach significance level in the crossmodal condition ($t(13) = 1.19$, $P = 0.254$).

Separate ANOVAs for the *unimodal* and *crossmodal conditions* revealed a marginal significant main effect of Speaker for the unimodal condition ($F(3,39) = 2.41$, $P = 0.091$) but failed to show any Speaker effect for the crossmodal condition ($F(3,39) = 0.75$, $P = 0.524$).

Post hoc *t*-tests revealed larger spatial attention effects for speaker 1 compared to speaker 2 for the unimodal condition. Furthermore, there was a marginal significant difference between attention effects at speakers 2 and 3 (Fig. 4e, bottom line). Neither reliable effects of spatial attention nor any gradient of spatial attention were observed for the crossmodal condition.

Positive spatial attention effects in this time epoch were significant at anterior-central clusters. Thus, we analyzed the spatial attention gradients for this time window at cluster L1 as well (see Fig. 4f). While spatial attention effects did not differ between speakers in neither the unimodal ($F(3,39) = 0.072$, $P = 0.96$) nor the crossmodal condition ($F(3,39) = 1.30$, $P = 0.289$) they differed significantly from zero at speakers 1, 2 and 3 in the crossmodal condition only (Fig. 4f, bottom line). A similar result pattern was observed for the anterior cluster R1.

Thus, crossmodal spatial attention effects had a broader spatial distribution than unimodal spatial attention effects.

Discussion

The present study was designed to test whether unimodal and crossmodal spatial attention effects arise from common or different spatial representations. An auditory–visual spatial attention paradigm was employed. Visual and auditory stimuli were presented in a random order from five different locations in the right hemifield. Participants had to detect either visual or auditory deviants at the innermost or the outmost right location. Spatial attention effects were assessed both behaviorally and with event-related potentials.

Localization performance was more precise for visual than auditory stimuli. While unimodal spatial attention effects started at 100 and 150 ms for auditory and visual ERPs, respectively, crossmodal attention effects were observed after 150 ms poststimulus in both modalities. Unimodal spatial attention gradients had a modality-specific distribution. Crossmodal spatial attention gradients were less precisely tuned than unimodal gradients.

The finding of crossmodal spatial attention effects both for auditory and visual ERPs replicates earlier reports (Eimer and Schröger 1998; Hillyard et al. 1984; Teder-Sälejärvi et al. 1999).

The focus of the present study was on gradients of spatial attention. Spatial attention effects on both behavioral measures (Downing and Pinker 1985; Mondor and Zatorre 1995) and ERPs have been found to fall off gradually from the centre of spatial attention to adjacent locations (Teder-Sälejärvi et al. 1999). The steepness of these gradients has been assumed to be a function of the spatial tuning of sensory neural networks activated during attentional orienting. For example, gradients of ERP spatial attention effects have been shown to be steeper for central positions in space (around zero degree azimuth, where sound localization is best) than for sound sources at peripheral positions (e.g., 90 degree azimuth, where sound localization is worse than in the centre) (Röder et al. 1999; Teder-Sälejärvi et al. 1999).

Spatial attention effects on early ERPs (<200 ms) have been considered to indicate a gain control mechanism modulating, i.e., increasing or decreasing, the excitability of sensory specific cortex (Hillyard et al. 1998). Thus, the width of the spatial attention gradient has been proposed to indicate the spatial tuning of sensory processing areas. For example, it has been shown that the spatial tuning of auditory sensory representations in peripheral space is more precise in congenitally blind than in sighted individuals (Röder et al. 1999) and for conductors than for other musicians (Münte et al. 2001).

In the present experiment, the first unimodal spatial attention effects in both the auditory and visual modality were broadly tuned. Thus, no difference between speakers in the size of the ERP spatial attention effect was observed for auditory spatial attention effects of time epoch 100–150 ms. Concordantly, visual spatial attention effects of the first three speakers differed from those of the fourth speaker but not among the first three speakers for time epoch 150–200 ms. ERP spatial attention effects of the second time window matched well with task performance in both modality conditions. Auditory spatial attention effects were significant at speaker 1 and 2 only (time epoch 175–225 ms) while (negative) visual spatial attention effects were observed over the posterior contralateral scalp for the first speaker only. This corresponds to the considerable number of false alarms for deviant sounds at speaker 2 while nearly errorless performance was observed in the visual task. It is however, not possible to claim that the first and second time epoch analyzed for auditory and visual ERPs reflects similar processes in the two modalities. Such correspondence between ERPs elicited by stimuli of different modalities is hard to access for sensory ERPs given the different functional organisation of sensory systems (see Luck 2005). Nevertheless, the fact that the final spatial tuning that was observed at sites located over cortex that is dominated by input of one modality (central recordings of auditory ERPs arise partially in temporal cortex; Näätänen 1992), correlated with the spatial precision of the modality system, suggests that, at least partially, non-identical spatial representations are used for orienting spatial attention in vision and audition (Macaluso and Driver 2004).

The question arising at this point of the discussion is whether crossmodal spatial attention effects are based on modality specific spatial representations or if at least partially different spatial representations are used for crossmodal interactions. The present findings seem to support the second view. Crossmodal spatial attention gradients were less precisely tuned than unimodal attention gradients. Indeed, hardly any spatial tuning was observed for crossmodal spatial attention effects. A difference of the size of the spatial attention effect between speaker 4 and the remaining central speakers was observed for auditory ERPs between 175 and 225 ms only. Thus, crossmodal spatial attention seems to be broadly distributed across space.

These findings are in line with results of Eimer et al. (2004) and Eimer and Van Velzen (2005). They reported that spatial tuning is more precise than shifting attention to one or the other hemifield. Since we presented all stimuli within one hemifield, we were able to replicate hemifield tuning of spatial attention both for unimodal and crossmodal conditions irrespectively of stimulus modality. Thus, the present study supports the conclusions of Eimer and Van Velzen (2005), that neither unimodal nor crossmodal spatial attention is "distributed diffusely across the entire hemifield" (Eimer and Van Velzen 2005, p. 402). As noted by Eimer and Van Velzen (2005) only studies with more tightly spaced locations allow deciding whether spatial tuning is less precise across than within modalities. Indeed, less precise crossmodal than unimodal spatial tuning is what we found in the present experiment that met the experimental requirements proposed by Eimer and Van Velzen (2005). Crossmodal spatial attention gradients were always broader than the corresponding unimodal spatial attention gradients. Though this conclusion was not always supported by an interaction of Speaker by Attended Modality, more specific follow up analyses for *both* modalities and for *all* analyzed time epochs are in line with this view.

Kadunce et al. (2001) noted that the highest multisensory enhancement in the superior colliculus is observed for the area of receptive field (RF) overlap for auditory and visual responses. However, multisensory interactions were observed for multisensory stimuli as well when the modality parts were not presented in the area of receptive overlap, i.e., when presented with a considerable spatial disparity. Thus, the borders of crossmodal spatial overlap seem to be determined by the borders of the unimodal RFs. These results suggest that unimodal spatial representations must be equal or smaller than the crossmodal RF. Our results are consistent with these findings although ERPs do not assess superior colliculus activity, at least not directly, and although auditory and visual stimuli were presented sequentially rather than simultaneously: Crossmodal spatial attention gradients were always broader than the corresponding unimodal spatial attention gradients.

It might be argued, that ERP attention *gradients* rather than ERP attention effects for stimuli at the attended speaker *only* were observed because we used an interstimulus interval of an average of 1000 ms which might have fostered switching attention between speakers. Moreover, it might further be argued that crossmodal attention effects and the broader gradient for cross- than for unimodal ERP attention effects might be due to switching attention from stimuli of the attended to stimuli of the unattended modality.

First, we decided to use an average ISI of 1000 ms since with short ISIs an extensive ERP overlap has to be expected. To compensate for the resulting loss in the signal to noise ratio with short ISIs a relatively large number of trials is needed (e.g., Röder et al. 1999; Teder-Sälejärvi and Hillyard 1998; Teder-Sälejärvi et al. 1999). Many researchers thus used longer, i.e., similar ISIs as we did in the present study, including 1000 ms (Eimer et al. 2001; Eimer and Driver 2000), 417–817 ms (Talsma and Kok 2001), 650–950 ms (Hötting et al. 2003). Using longer ISIs has another advantage: it is easier to unequivocally assign a response to a stimulus. In crossmodal spatial attention tasks with trial by trial cueing paradigms researchers have used S1–S2 intervals varying between 100 and 800/1000 ms (e.g., Eimer and Schröger 1998; Eimer and Van Velzen 2002; McDonald et al. 2003).

Hansen and Hillyard (1988) directly compared the (auditory) ND (negative difference) effect in spatial attention experiments with short (250–550 ms) and long (1250–2750 ms) ISIs. The ND latency was shorter and its amplitude was smaller with short ISIs. However, an ND was observed irrespectively of the ISI used. In sum, similar uni- and crossmodal attention effects have been reported with both short and long interstimulus intervals.

However, long ISIs might have encouraged participants to switch attention between locations resulting in attention gradients as observed in the present and previous studies (Pauli and Röder 2008; Röder et al. 1999; Teder-Sälejärvi and Hillyard 1998; Teder-Sälejärvi et al. 1999). We consider an attention switch account for the present results as unlikely because this account cannot easily explain why the spatial distribution of spatial attention effects for the unimodal and crossmodal conditions are not the same, i.e., why the spatial extent for within vs. crossmodal "attention switches" would differ. Moreover, attention switches due to long ISIs would have to be expected for the attended peripheral speaker condition as well which would result in a cancelation of any observable attention effect at the central speakers. Finally, an attention switch account would have to find an explanation for the robust intermodal attention effects obtained in the present study (see footnote 1). The significant intermodal attention effects also argue against serious carry-over effects due to the within participant design. We varied the attended modality within participants since continuously reorienting attention within and between sensory channels is what people have to do in everyday life. Importantly, within (e.g., Eimer and Schröger 1998; Eimer and Van Velzen 2002; Hötting et al. 2003; McDonald et al. 2003; Talsma et al. 2007) and between (Eimer et al. 2004; Teder-Sälejärvi et al. 1999) participant designs have reported similar crossmodal attention effects.

In sum, we found both unimodal and crossmodal gradients of spatial attention. Unimodal spatial ERP gradient correlated with the spatial resolution of the modality. Crossmodal spatial gradients were always broader than the corresponding unimodal spatial gradients and extended almost over the complete central area covered by the speaker/light positions, irrespectively of stimulus modality.

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