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# Can attention be directed to opposite locations in different modalities? An ERP study

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**Abstract**

**Objectives**: An event-related brain potential (ERP) study investigated whether spatially selective processing in vision and audition is controlled by a single supramodal system or by independent modality-specific systems.

**Methods**: Event-related brain potentials were recorded in response to visual and auditory stimuli at attended and unattended locations. In the 'Attend Same' condition, attention was directed to a single location in both modalities, while in the 'Attend Opposite' condition, visual and auditory attention had to be directed into opposite directions.

**Results**: Sensory-specific effects of attention on visual and auditory ERPs reflecting attentional modulations of perceptual processing were obtained in the 'Attend Same' condition, but not the 'Attend Opposite' condition. Beyond 200 ms post-stimulus, attentional ERP effects were also found in the 'Attend Opposite' condition.

**Conclusion**: Results are inconsistent with the view that spatially selective processing is controlled by independent modality-specific systems. Effects of spatial attention on visual and auditory perceptual processing are closely linked, suggesting the existence of a supramodal attentional control system. At post-perceptual levels, attentional control may be more flexible.

*Keywords:* Visual spatial attention; Auditory spatial attention; Cross-modal attention; Event-related brain potential

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## 1. Introduction

Perception and the adaptive control of behaviour depend on the integration of information from different senses. When trying to follow a speaker in a noisy environment, attending to the speaker's voice may be as relevant as attending to the speaker's lip movements and gestures. In such a situation, attentional selectivity has to be co-ordinated across modalities by directing the focus of attention to sensory information stemming from different modalities, but from the same location in space. For a full understanding of attentional processing, it is necessary to study mechanisms involved in the control of spatial attention across modalities. While experimental research on spatial attention was traditionally focused on spatially selective processes within single modalities, a number of recent behavioural and electrophysiological studies have begun to investigate cross-modal links in spatial attention (see Driver and Spence, 1998, for an overview).

Cross-modal links between endogenous (voluntary) visual and auditory spatial attention were first investigated by Buchtel and Butter (1988), and more recently by Spence and Driver (1996), in a situation where a centrally presented arrow cue indicated the likely location of target stimuli of one modality. Target stimuli of the other modality were presented less frequently (they appeared on about 25% of all trials), and were more likely at the uncued side. The results suggested a symmetrical link between auditory and visual endogenous attention: when the cue indicated the likely location of auditory targets, visual discrimination was faster when visual targets were presented at cued locations. When the location of visual targets was cued, auditory discrimination was faster at cued than at uncued locations.

Eimer and Schröger (1998) investigated whether cross-modal links in endogenous spatial attention would be reflected in modulations of event-related brain potentials (ERPs). Single visual or auditory stimuli were presented randomly, and with equal probability, in the left or right visual field. Participants had to attend to audition or to vision (relevant modality) in order to respond to infrequently presented targets (slightly longer tones or light flashes) in this modality when these were presented at an attended location. The relevant modality remained constant throughout an experimental block, while the to-be-attended location was indicated by a pre-cue at the beginning of each

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trial. When audition or vision were relevant, enhanced negativities between 160–280 ms following stimulus onset were found for stimuli at attended as compared to unattended locations. Most importantly, similar effects were also observed for visual and auditory stimuli when this modality was irrelevant, although these effects were considerably smaller than for the relevant modality. Similar findings have been reported by Hillyard et al. (1984), suggesting the existence of cross-modal links between vision and audition in endogenous spatial attention.

These results leave open the question as to how spatial attention is co-ordinated across modalities. One possibility is that there is a single supramodal attentional system that operates in co-ordinates of external space, independently of target modality, and controls shifts of spatial attention for all modalities (see Farah et al., 1989, for such a view). Such a system might depend on the activity of multisensory neurons that have been found in cortical and subcortical areas in the cat (Meredith and Stein, 1986) and primate brain (Morrell, 1972; Rizzolatti et al., 1981), including the superior colliculus (see Stein and Meredith, 1993, for an overview). Alternatively, spatial attention may operate in a strictly modality-specific fashion. In this view, cross-modal links in spatial attention result from spatial synergies between separate visual and auditory sub-systems, rather than from spatially selective processing within a single attentional control system (see Spence and Driver, 1996, for such a 'separable-but-linked systems' account).

It is important to distinguish between attentional control mechanisms responsible for directing attention to locations of external space, and the resulting effects of attentional orienting on the processing of visual or auditory stimuli (see LaBerge, 1995). The orienting of spatial attention may have consequences for visual and auditory perceptual processing which will necessarily manifest themselves in modality-specific brain regions. Evidence for such 'early' effects of spatial attention comes from studies where ERPs elicited by stimuli at attended and unattended locations were compared. In vision, spatial attention modulates the amplitudes of sensory-specific lateral posterior P1 and N1 components, presumably indicating intraperceptual sensory gating mechanisms (Mangun and Hillyard, 1991; Eimer, 1993; Mangun, 1995; Eimer, 1998; for overviews). In audition, stimuli at attended locations elicit an enhanced negativity (Nd) when compared to stimuli at unattended locations. The first phase of this effect (early Nd) is assumed to reflect attentional modulations of sensory-specific brain areas (Näätänen and Michie, 1979; Woods et al., 1991; Näätänen, 1992; for an overview). In both modalities, these early attentional effects are followed by a sustained negativity for attended as compared to unattended stimuli (late Nd) that may be modality-unspecific and reflect post-perceptual processing (Alho et al., 1987; Eimer, 1996). The fact that spatial attention can affect perceptual processing within modality-specific brain areas does not imply that the control of spatial selectivity is a modality-specific phenomenon. It is equally compatible with the idea that spatial orienting processes in vision and audition are controlled by a common supramodal system.

One way to test whether spatial attention is controlled by modality-specific sub-systems or within a single supramodal system, is to study whether attention can be simultaneously shifted into opposite directions within different modalities. If spatial selectivity was controlled by a supramodal system, visual and auditory attention would necessarily shift together, and directing visual and auditory attention to opposite locations should be impossible. If the control of spatial attention was modality-specific, it should be possible to 'split' attentional selectivity between modalities, and to simultaneously attend to visual stimuli on the left, and auditory stimuli on the right, or vice versa. This has been investigated by Spence and Driver (1996) in experiments where participants had to respond to visual and auditory targets when about 80% of targets in one modality appeared on one side and about 80% of targets in the other modality appeared on the other side. Under conditions where these spatial probabilities were indicated on a trial-by-trial basis by a centrally presented pre-cue, no reliable attentional effects were observed, as would be predicted by the view that attentional control is strictly supramodal. In contrast, when the likely target side for each modality was constant for an entire block (Spence and Driver, 1996, Experiment 7), significant effects of spatial attention were obtained for both modalities, as reaction times (RTs) were about 20 ms faster for visual and auditory targets at expected locations. This result suggests that visual and auditory attention can be directed simultaneously to opposite locations, and is thus, incompatible with a strictly supramodal attentional system. However, attentional RT effects were 3 times larger in a control condition where the same side was most likely for both modalities, and visual and auditory attention could be directed to a common location. This seems inconsistent with a strong version of the hypothesis that visual and auditory attention operate within separate sub-systems, which would imply that attentional orienting processes within one modality are entirely independent from attentional processes within another modality.

In summary, the above experiments remain inconclusive as to whether the control of spatial attention operates in a modality-specific or a supramodal fashion. Spence and Driver (1996) found attentional effects on performance when visual and auditory attention were directed to opposite locations, but only under sustained attention conditions, and these effects were much larger when a single location was attended in vision and audition. Eimer and Schröger (1998) obtained ERP modulations suggesting the existence of cross-modal links in spatial attention in a trial-by-trial cueing situation, but these effects were attenuated for the secondary modality. It is possible that there are spatial synergies between visual and auditory attention, but that such links can be overcome when this is required by experimental circumstances, as when response relevant auditory and visual stimuli are more likely to be presented on opposite sites. Under such conditions, modality-specific attentional control mechanisms may operate independently.

The aim of the present experiment was to obtain electrophysiological evidence to decide whether the control of spatial attention is modality-specific or supramodal. Effects of spatial attention on visual and auditory ERPs in a situation where participants attended to a common location in both modalities were compared to effects obtained when visual and auditory attention had to be directed to opposite hemifields. Single visual or auditory target and non-target stimuli were presented randomly and equiprobable in the left or right visual field, and participants had to respond to visual and auditory targets when they appeared at a specific location. In the 'Attend Same' condition, this relevant location was identical for visual and auditory stimuli (left or right side). In the 'Attend Opposite' condition, the task was to detect auditory targets on the left, and visual targets on the right, or vice versa. ERPs were computed for visual and auditory non-target stimuli at attended and unattended locations in these two task conditions, and effects of spatial attention were measured by comparing ERP waveforms elicited by stimuli at attended locations to ERPs elicited by stimuli at unattended locations. If attentional control was completely modality-specific, thus allowing simultaneous shifts of visual and spatial attention into opposite directions, one would expect to find similar effects of spatial attention on ERP waveforms in the 'Attend Same' and 'Attend Opposite' condition. Modulations of ERP waveforms indicating attentional effects on perceptual processing (enhanced P1 and N1 components elicited by attended visual stimuli; early Nd effects for attended auditory stimuli), as well as later attentional Nd effects, should be present and of comparable magnitude in both task conditions. In contrast, the idea that spatial attention is controlled by a supramodal system implies that attentional effects should be fundamentally different in these two conditions. While attentional modulations of visual and auditory ERPs should be present in the 'Attend Same' condition, no spatially selective processing should be possible in the 'Attend Opposite' condition, which should be reflected in the absence of attentional effects on ERPs.

## 2. Materials and methods

### 2.1. Participants

Twelve paid volunteers participated in the experiment. One of them had to be excluded because of poor eye fixation control, another because of excessive alpha wave activity. Thus 10 participants (5 females), aged 22–38 years (mean age 29 years) remained in the sample. All participants were right-handed and had normal, or corrected to normal vision.

### 2.2. Stimuli and apparatus

Participants were seated in a dimly lit, electrically shielded and sound attenuated chamber, with response buttons under their left and right hands. Auditory stimuli consisted of bursts of white noise, digitally filtered with a bandpass from 100–10, 000 Hz and were delivered from two loudspeakers positioned at eyelevel 15° to the left and to the right of the participants' straight-ahead line of sight, at an approximate distance of 200 cm. Visual stimuli were light flashes presented from small light bulbs attached directly in front of the loudspeakers. All non-target stimuli had a duration of 100 ms. The auditory target stimulus had a duration of 150 ms, and the visual target stimulus had a duration of 250 ms.

### 2.3. Procedure

The experiment was divided into two parts ('Attend Same' and 'Attend Opposite') consisting of 8 blocks, resulting in a total of 16 experimental blocks. Single auditory or visual stimuli were presented on the left or right side, and the inter-trial interval between stimulus offset and the onset of the next stimulus was 1000 ms. Each block consisted of 84 non-target and 28 target trials, resulting in a total of 112 trials per block. Block duration was 2'6''. For both target and non-target trials, all combinations of stimulus modality (visual vs. auditory) and location (left vs. right) were equiprobable. In 'Attend Same' blocks, participants were instructed to direct their attention to the left or to the right side and press a button with the left or right hand if they detected visual or auditory target stimuli at the attended location. The to-be-attended side and the response hand were specified prior to each block, and were varied between blocks. Participants received two blocks for each of the 4 possible combinations of attended location (left vs. right) and response hand (left vs. right). In 'Attend Opposite' blocks, participants were instructed to direct their visual and auditory attention to opposite sides of the visual field in order to detect visual and auditory targets presented at these locations. In 4 blocks, responses were required to auditory targets on the left side and visual targets on the right side, in the other 4 blocks, right auditory targets and left visual targets were response relevant. Again, instructions regarding attention and response hand were given prior to each block, and were varied between blocks. Participants received two blocks for each of the 4 possible combinations of attended locations (visual-left/auditory-right vs. visual-right/auditory-left) and response hand (left vs. right). The order in which the two experimental parts (Attend Same vs. Attend Opposite) were delivered was balanced across participants. Participants were instructed to respond as quickly and accurately as possible and to maintain central eye fixation. To make them familiar with the specific task requirements, one or two training blocks were run at the beginning of both experimental parts.

### 2.4. Recording and data analysis

EEG was recorded with Ag–AgCl electrodes from Fz, Cz, and Pz (according to the 10–20 system), from PL and PR (located halfway between Pz and each ear canal), and from OL and OR (located halfway between $O_1$ and $T_5$, and $O_2$ and $T_6$, respectively). All electrodes were referenced to the tip of the nose. The horizontal EOG was recorded bipolarly from the outer canthi of both eyes, the vertical EOG from electrodes above and below the right eye. The impedance for the EOG electrodes was kept below 10 kΩ, and for all other electrodes below 5 kΩ. The amplifier bandpass was 0.1–40 Hz. EEG and EOG were sampled with a digitization rate of 200 Hz and stored on disk. Reaction times were measured for each response relative to stimulus onset.

EEG and EOG were epoched offline into 800 ms periods starting 100 ms prior and ending 700 ms after the onset of the stimulus. Trials with eyeblinks (VEOG exceeding ± 60 μV relative to 100 ms pre-stimulus baseline), horizontal eye movements (HEOG exceeding ± 30 μV relative to baseline), other artefacts (a voltage exceeding ± 100 μV at any electrode location relative to baseline), or overt response errors were excluded from analysis. The EEG to the non-target stimuli was averaged separately for all combinations of task (Attend Same vs. Attend Opposite), attention (attended vs. unattended location), stimulus modality (visual vs. auditory), and stimulus side (left vs. right), resulting in 16 ERP waveforms for each participant and electrode site.

All ERP measures were taken relative to the mean voltage of the 100 pre-stimulus baseline interval. For visual ERPs, mean amplitude values were computed for the following post-stimulus latency windows: P1 (80–120 ms for contralateral posterior sites, and 100–140 ms for ipsilateral posterior sites), N1 (160–200 ms, for lateral posterior sites), early Nd (160–210 ms, for midline electrodes), and late Nd (210–280 ms, for lateral posterior and midline sites). For auditory ERPs, mean amplitudes were computed for midline sites within the early Nd and late Nd latency windows. Repeated measures ANOVAs were performed for visual and auditory ERPs at midline electrodes on mean amplitude values for the factors task, attention, stimulus side and electrode location (Fz vs. Cz vs. Pz). When appropriate, a Greenhouse–Geisser adjustment to the degrees of freedom was performed. Additional ANOVAs were performed for visual ERPs at ipsilateral and contralateral parietal and occipital electrodes. For the behavioural data, repeated measures ANOVAs were performed on response latencies and hit rates for the factors task, stimulus modality, stimulus side and response hand.

## 3. Results

### 3.1. Behavioural performance

For the response time data, a main effect of task ($F(1,9) = 8.73$; $P < 0.016$) was obtained, as RTs were faster in the ‘Attend Same’ condition (646 ms) than in the ‘Attend Opposite’ condition (688 ms). RTs to visual targets and auditory targets were 672 ms and 662 ms, respectively, and this difference was not significant. Task × response hand and modality × response hand interactions were obtained ($F(1,9) = 8.85$; $P < 0.016$; $F(1,9) = 9.83$; $P < 0.012$, respectively). Right responses were significantly faster than left responses in the ‘Attend Same’ condition (628 ms vs. 664 ms; $t(9) = 3.10$; $P < 0.013$) and for auditory targets (648 ms vs. 675 ms; $t(9) = 2.33$; $P < 0.045$), but not in the ‘Attend Opposite’ condition (691 ms vs. 685 ms) and for visual targets (671 ms vs. 674 ms).

Participants responded to 88.3% of the visual targets and to 80.6% of all auditory targets, as reflected by a main effect of stimulus modality on hit rate ($F(1,9) = 7.22$; $P < 0.025$). Hit rates did not differ significantly between the ‘Attend Same’ and ‘Attend Opposite’ conditions (86.4% vs. 82.6%). False alarms to visual and auditory non-targets occurred in 0.9% and 0.2% of all trials in the ‘Attend Same’ condition, and in 1.3% and 0.6% of all ‘Attend Opposite’ trials.

### 3.2. Visual ERPs at lateral posterior electrodes

Fig. 1 shows grand-averaged ERPs obtained for attended and unattended visual stimuli at contralateral and ipsilateral parietal and occipital electrodes in the ‘Attend Same’ and ‘Attend Opposite’ conditions. Attention affected occipital P1 amplitude in the ‘Attend Same’ condition at contralateral sites ($F(1,9) = 14.52$; $P < 0.004$) as well as ipsilateral sites ($F(1,9) = 7.26$; $P < 0.025$), with larger P1 components for attended, as compared to unattended, stimuli (Fig. 1, top). Significant attentional P1 modulations were also obtained at contralateral parietal sites ($F(1,9) = 5.16$; $P < 0.049$). In contrast, no such effects were present in the ‘Attend Opposite’ condition (Fig. 1, bottom). This difference in attentional P1 modulations between the two task situation was reflected in significant task × attention interactions for contralateral and ipsilateral occipital electrodes ($F(1,9) = 19.70$; $P < 0.002$; $F(1,9) = 6.11$; $P < 0.035$, respectively).

Attention affected N1 amplitude at contralateral parietal sites in the ‘Attend Same’ condition ($F(1,9) = 7.05$; $P < 0.026$). Although a similar amplitude modulation is apparent in Fig. 1 at contralateral occipital electrodes, this difference failed to reach statistical significance. No significant effects of attention on N1 were obtained in the ‘Attend Opposite’ condition, and at ipsilateral electrodes in the ‘Attend Same’ condition.

Main effects of attention were obtained at contralateral as well as ipsilateral parietal and occipital electrodes in the late Nd interval (all $F(1,9) > 12.0$; all $P < 0.007$), reflecting enhanced negativities for attended, as compared to unattended, stimuli within this time range (see Fig. 1). Interactions between task and attention at contralateral and

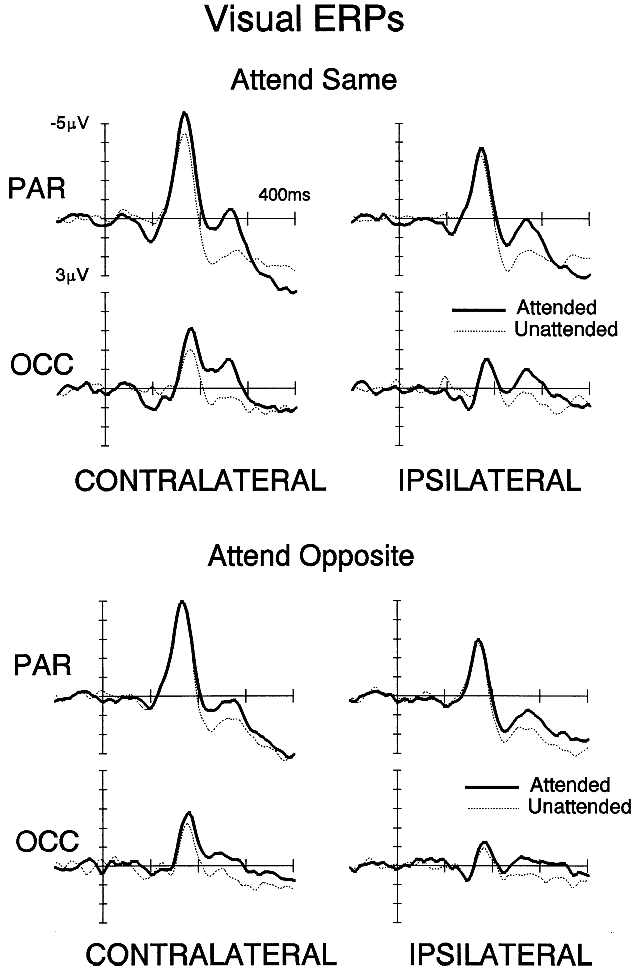

Fig. 1. Grand-averaged ERPs elicited by visual non-target stimuli in the 'Attend Same' condition (top) and the 'Attend Opposite' condition (bottom) at parietal (PAR) and occipital (OCC) sites contralateral and ipsilateral to the side of stimulus presentation for stimuli at attended locations (thick lines) or at unattended locations (thin dashed lines).

ipsilateral parietal sites ($F(1,9) = 5.50$; $P < 0.044$; and $F(1,9) = 7.34$; $P < 0.024$) and an almost significant task × attention interaction at contralateral occipital electrodes ($F(1,9) = 5.0$; $P < 0.052$), indicated that these effects were generally larger in the 'Attend Same' condition. However, significant attentional modulations were also present in the 'Attend Opposite' condition at all ipsilateral and contralateral posterior sites (all $F(1,9) > 6.45$; all $P < 0.032$).

### *3.3. Visual ERPs at midline sites*

Fig. 2 shows grand-averaged ERPs obtained for attended and unattended visual stimuli at midline electrodes in the 'Attend Same' and 'Attend Opposite' conditions, together with the resulting attended-unattended difference waveforms. No significant effects of attention were obtained for the early Nd time window. In the late Nd interval (210–280 ms post-stimulus), ERPs were more negative for attended as compared to unattended stimuli. This was reflected in a main effect of attention ($F(1,9) = 7.98$; $P < 0.020$), which was accompanied by an electrode location × attention interaction ($F(2,18) = 9.78$; $P < 0.002$; $\epsilon = 0.940$) and an almost significant task × attention interaction ($F(1,9) = 4.51$; $P < 0.063$). In addition, a significant 3-way interaction (task × electrode location × attention: $F(2,18) = 3.86$; $P < 0.049$; $\epsilon = 0.855$) was obtained. To further clarify this pattern of results, attentional Nd effects were tested separately for each midline electrode and task condition with one-tailed paired $t$ tests. Significant Nd effects were present for all midline electrodes in the 'Attend Same' condition, and were largest at Cz (see Fig. 2, right). In the 'Attend Opposite' condition, the attentional Nd effect was significant only at Cz ($t(9) = 2.78$; $P < 0.011$), and approached significance at Pz ($t(9) = 1.76$; $P < 0.056$). At electrode Cz, the attentional Nd effect was significantly larger in the 'Attend Same' than in the 'Attend Opposite' condition ($t(9) = 2.58$; $P < 0.030$, two-tailed).

### *3.4. Auditory ERPs at midline sites*

Fig. 3 shows the ERPs obtained for attended and unattended auditory stimuli at midline electrodes in the 'Attend Same' and 'Attend Opposite' conditions, together with the resulting attended-unattended difference waveforms. A main effect of attention ($F(1,9) = 9.03$; $P < 0.015$) was present in the early Nd interval (160–210 ms post-stimulus), and was accompanied by task × attention and electrode location × attention interactions ($F(1,9) = 6.39$; $P < 0.032$; and $F(2,18) = 6.56$; $P < 0.012$; $\epsilon = 0.813$). As can be seen from Fig. 3 (right), attentional Nd effects were present in the 'Attend Same' condition, and were largest at Cz, while no such effects seem to be elicited in the 'Attend Opposite' condition. This was further substantiated by comparing ERPs to attended and unattended stimuli in each task condition at individual midline electrodes with one-tailed paired $t$ tests. In the 'Attend Same' condition, significant effects were obtained for all 3 midline sites, while no such effects were present for the 'Attend Opposite' condition.

In the late Nd interval (210–280 ms post-stimulus), a main effect of attention ($F(1,9) = 14.88$; $P < 0.004$) was obtained together with task × attention and electrode location × attention interactions ($F(1,9) = 7.49$; $P < 0.023$; and $F(2,18) = 11.45$; $P < 0.0003$; $\epsilon = 0.682$). Attentional Nd effects were more pronounced in the 'Attend Same' condition, and were again largest at Cz (Fig. 3, right). Additional one-tailed paired $t$ tests conducted for each task condition at single midline sites revealed significant attentional effects at Fz, Cz and Pz in the 'Attend Same' condition. In the 'Attend Opposite' direction, the Nd effect was significant only at Cz ($t(9) = 2.55$; $P < 0.015$), and approached significance at Pz ($t(9) = 1.68$; $P < 0.064$).

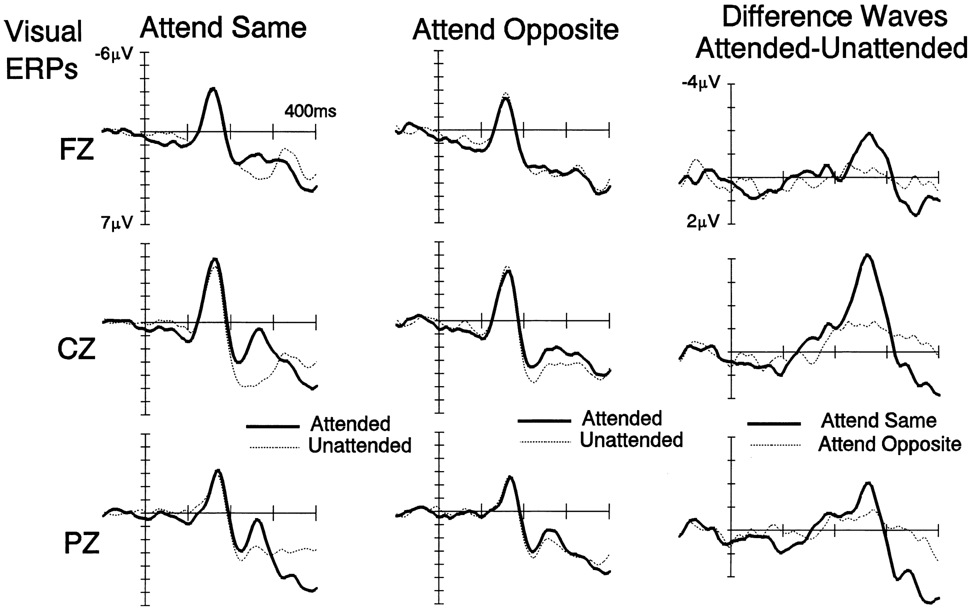

Fig. 2. Grand-averaged ERPs elicited by attended and unattended visual stimuli in the 'Attend Same' condition (left) and in the 'Attend Opposite' condition (middle) at midline electrodes. Right side: difference waveforms obtained at midline electrodes by subtracting ERPs to unattended stimuli from ERPs to attended stimuli in the 'Attend Same' condition (thick lines) and in the 'Attend Opposite' condition (thin dashed lines).

## 4. Discussion

The aim of the present study was to investigate whether spatially selective processing is controlled by a single supramodal system or by independent modality-specific subsystems. Participants had to detect infrequently presented visual and auditory targets at attended locations in an 'Attend Same' condition, where the relevant location was identical for both modalities, and in an 'Attend Opposite' condition, where these locations were on opposite sides for vision and audition. If the control of spatial attention was strictly modality-specific, similar attentional modulations of ERP waveforms should have been observed in these two conditions, as attentional processes within one modality would operate independently from attentional processes within the other modality. If spatial attention was a supra-

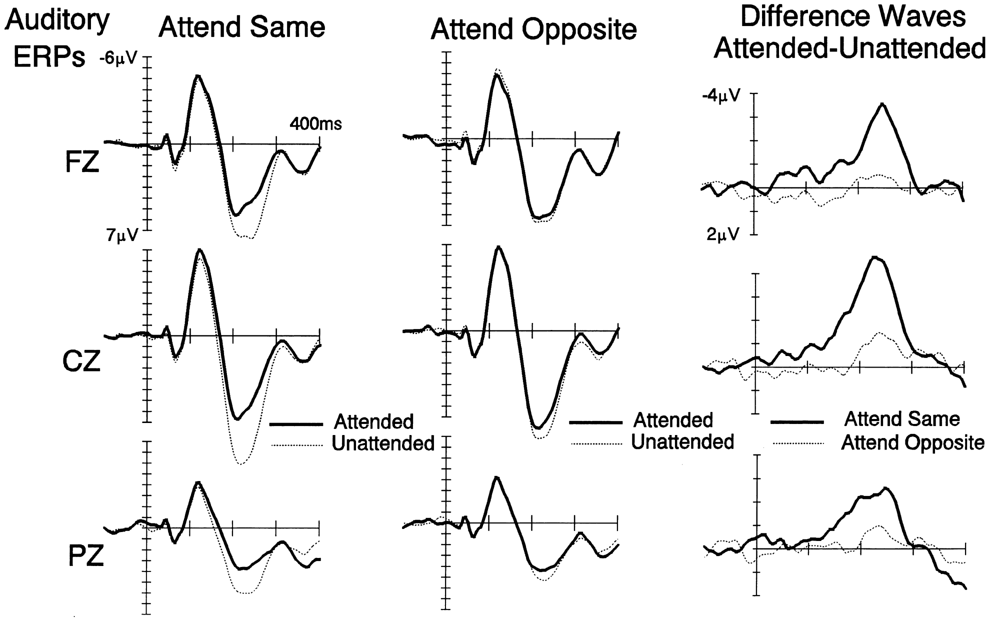

Fig. 3. Grand-averaged ERPs elicited by attended and unattended auditory stimuli in the 'Attend Same' condition (left) and in the 'Attend Opposite' condition (middle) at midline electrodes. Right side: difference waveforms obtained at midline electrodes by subtracting ERPs to unattended stimuli from ERPs to attended stimuli in the 'Attend Same' condition (thick lines) and in the 'Attend Opposite' condition (thin dashed lines).

modal phenomenon, attentional ERP effects should have been found for the ‘Attend Same’ condition, but not for the ‘Attend Opposite’ condition, as it would be impossible to direct visual and auditory attention simultaneously to opposite locations.

Most of the ERP results obtained in the present study favour the latter account. For visual stimuli, attentional modulations of sensory-evoked P1 components were observed in the ‘Attend Same’ condition at contralateral and ipsilateral occipital electrodes as well as at contralateral parietal sites. In contrast, no such effects were obtained in the ‘Attend Opposite’ condition, and this difference was reflected in task × attention interactions. Significant attentional N1 modulations were found at contralateral parietal sites in the ‘Attend Same’ condition, but were absent in the ‘Attend Opposite’ condition. In the late Nd interval, attentional ERP modulations were more pronounced in the ‘Attend Same’ condition at lateral parietal electrodes as well as at Cz. However, attentional effects were also found for the ‘Attend Opposite’ condition in the late Nd interval at lateral posterior electrodes as well as at Cz. For auditory stimuli, earlier and larger attentional Nd effects were observed in the ‘Attend Same’ condition. In the early Nd interval (160–210 ms post-stimulus), enhanced negativities for attended stimuli were elicited in the ‘Attend Same’ condition, but not in the ‘Attend Opposite’ condition, as reflected in a task × attention interaction. In the late Nd interval, attentional effects were more pronounced in the ‘Attend Same’ condition. While attentional Nd effects were present at all midline electrodes in the ‘Attend Same’ condition, they were significant at Cz and approached significance at Pz in the ‘Attend Opposite’ condition.

These results suggest that ‘early’ sensory-specific effects of spatial attention on visual ERPs (P1 amplitude modulations) and auditory ERPs (early Nd effects) are elicited when visual and auditory attention can be directed to a single location, but not when opposite sides have to be attended in vision and audition. This is inconsistent with the view that spatial attention is controlled by strictly modality-specific sub-systems, which predicts that attentional effects within one modality are independent from attentional orienting processes within another modality. Audition and vision seem closely linked with respect to the control of spatially selective perceptual processing. One could interpret this as evidence for strong spatial synergies in the control of visual and auditory attention, or as support for the idea that endogenous spatial attention is controlled by a supramodal system, although it is unclear how to decide experimentally between these two possibilities. The observation that response times were about 40 ms faster in the ‘Attend Same’ condition also seems inconsistent with the idea that attentional control is a modality-specific phenomenon. If attentional orienting processes within single modalities were entirely independent, responses to visual and auditory targets should not be delayed in the ‘Attend Opposite’ condition. The RT differences observed between the two task conditions are more in line with the view that spatial attention is controlled by a supramodal system, so that shifts of visual-spatial and auditory-spatial attention are necessarily coupled, making orienting visual and auditory attention into opposite locations impossible. The resulting absence of spatially selective processing in the ‘Attend Opposite’ condition would explain the absence of attentional effects on sensory evoked visual ERP components and early Nd effects for auditory ERPs as well as the fact that responses to visual and auditory targets were delayed in this condition.

Instead of maintaining a diffuse attentional state in the ‘Attend Opposite’ blocks, participants may have attended to the relevant location for auditory stimuli on some trials, and to the relevant location for vision on other trials. Since the ERP waveforms and RT data were based on averaging across trials, this strategy would have resulted in the absence of systematic attentional effects on visual and auditory ERPs as well as in delayed RTs for the ‘Attend Opposite’ condition. Such an attentional allocation strategy can be seen as a direct consequence of the fact that spatial attention cannot be directed to opposite locations in different modalities, and would thus be perfectly consistent with the supramodal control of attentional selectivity.

The ERP effects observed in the late Nd interval do, however, provide some positive evidence for the presence of independent modality-specific attentional processes. Although late Nd effects were generally larger in the ‘Attend Same’ condition, significant attentional effects were also present in the ‘Attend Opposite’ condition at lateral posterior sides for visual stimuli and at Cz for visual and auditory stimuli. It is likely that these late Nd effects reflect attentional processes at post-perceptual levels. One may assume that the small attentional effects on RT obtained by Spence and Driver (1996) when visual and auditory targets were likely to be presented at opposite locations are a reflection of this type of ‘late’ attentional selectivity. The present ERP results may thus help to qualify the idea advocated by Spence and Driver (1996) that modality-specific attentional control systems are ‘separable, but linked’. They are closely linked with respect to the control of attentional modulations of perceptual processing, but partially separable with respect to post-perceptual attentional effects.

In summary, the present study showed that ‘early’ effects of attention on visual and auditory ERPs reflecting attentional modulations of perceptual processing are elicited when visual and spatial attention are directed to a common location, but not when they are directed to opposite directions. ‘Later’ attentional Nd effects are more pronounced in the former situation, but may also be obtained in the latter condition. Spatially selective modulations of perceptual processes in vision and audition are closely linked, possibly reflecting the existence of a supramodal attentional control system.

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