Psychophysiology, 35 (1998), 313–327. Cambridge University Press. Printed in the USA.

ERP effects of intermodal attention and cross-modal links in spatial attention

MARTIN EIMER[a] AND ERICH SCHRÖGER[b]

[a]Department of Experimental Psychology, University of Cambridge, England
[b]Institut für Allgemeine Psychologie, Universität Leipzig, Germany

Abstract

Effects of intermodal attention AND of cross-modal links in spatial attention on visual and auditory event-related potentials (ERPs) were investigated in two experiments where participants had to attend to one stimulus modality (audition or vision) to respond to infrequently presented targets whenever these were presented at a relevant location (indicated by a cue). The ERP effects of intermodal attention (measured by comparing the ERPs elicited by visual and auditory stimuli when the respective modality was relevant or irrelevant) were differently distributed in vision and audition, suggesting that intermodal attention operates by a selective modulation of modality-specific areas. Similar ERP effects of spatial attention (measured by comparing the ERPs to stimuli at cued and uncued locations) were elicited at midline electrodes in vision and audition. With one notable exception, these effects were also present when attention was directed within the other modality, suggesting the existence of cross-modal links between vision and audition in the control of transient spatial attention.

Descriptors: Visual spatial attention, Auditory spatial attention, Event-related brain potentials, Intermodal attention, Cross-modal attention, Nd

Most research devoted to the study of selective attention has focussed exclusively on selective processes within a specific modality. Although such studies may be useful in discovering mechanisms of selective attention within a given modality, they will not be able to determine whether selective processes within different modalities are entirely modality specific or at least partially subserved by common supramodal mechanisms. Event-related brain potentials (ERPs) may provide a useful tool for studying this question. If a specific attentional process were completely supramodal, analogous ERP effects of this process could be expected within different stimulus modalities. In contrast, if such a process were entirely modality specific, different ERP effects should be observed within different modalities. In the present study, two different attentional processes (the selection of a relevant stimulus modality and the selection of a relevant stimulus location) were investigated in the auditory and visual modality to find out whether these processes are primarily mediated by supramodal mechanisms or whether they are largely modality specific. Participants were instructed to attend to one stimulus modality and to ignore the other stimulus modality (intermodal attention) to detect infrequently presented target stimuli at a relevant location that was indicated by a cue at the beginning of each trial (spatial attention).

Directing attention to a specific modality results in performance benefits when compared with a situation where attention is divided between modalities (cf. Posner, Nissen, & Ogden, 1978, Experiment 4; Spence & Driver, 1997). Several ERP studies have investigated whether such effects are due to modality-specific attentional operations or to supramodal mechanisms (cf. Alho, Woods, & Algazi, 1994; Alho, Woods, Algazi, & Näätänen, 1992; Woods, Alho, & Algazi, 1992). For example, Woods et al. (1992, Experiment 2) presented streams of visual and auditory stimuli (50 ms duration, interstimulus interval of 200–400 ms), instructed participants to detect deviant events within one modality, and compared the visual and auditory ERPs elicited when the respective modality was either attended or unattended. In vision, intermodal attention affected the ERPs primarily at posterior electrodes, with enhanced negativities elicited by relevant visual stimuli. In contrast, the effects of intermodal attention on auditory ERPs were frontocentrally distributed, with an enhanced negativity that was followed by an enhanced positivity elicited by relevant tones. According to Woods et al. (1992), this pattern of results suggests that the ERP effects of intermodal attention were generated in visual and auditory sensory areas. Although these results may indicate that intermodal attention in vision and audition is largely modality specific, there is one potential confounding in the Woods et al. study that needs consideration. Whereas auditory stimuli were delivered over headphones, visual stimuli were presented on a computer monitor placed in front of the participants. Because stimuli of different modalities were presented from different positions, attention may have been directed not only to a specific modality but also to the

This research was supported by the Max-Planck-Institute for Psychological Research and by a grant from the Deutsche Forschungsgemeinschaft (No. Ei 266/4-1).

We thank Steve Luck and two anonymous reviewers for helpful comments, Andreas Widmann for technical support, and Renate Tschakert, Monika Fahn, and Verena Pritschow for their help in conducting the experiments.

Address reprint requests to: Martin Eimer, Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, England. E-mail: me209@cam.ac.uk.

positions where the relevant stimuli were to appear (cf. Spence & Driver, 1997, for a detailed discussion of this issue). It is therefore not clear whether the ERP results observed by Woods et al. are a pure measure of intermodal attention or whether they also reflect effects related to spatial expectations.

Numerous studies have investigated spatial attention in vision and audition in trial-by-trial cueing paradigms, where a spatially informative cue is presented at the beginning of each trial and participants are instructed to attend to the location indicated by the cue without moving their eyes (cf. Posner et al., 1978). Stimuli at cued (attended) locations are detected with higher speed and accuracy than are stimuli presented at uncued locations. Such effects have been reported in the visual modality (cf. Downing, 1988; Müller & Rabbitt, 1989; Luck et al., 1994; Posner, Snyder, & Davidson, 1980) and with auditory stimuli (cf. Bédard, El Massioui, Pillon, & Nandrino, 1993; Quinlan & Bailey, 1995; Robin & Rizzo, 1992; Spence & Driver, 1994). Recent ERP studies employing trial-by-trial cueing have found systematic effects of spatial attention for auditory stimuli (Schröger, 1993, 1994; Schröger & Eimer, 1993, 1997) and for visual stimuli (Eimer, 1993, 1994, 1996; Mangun & Hillyard, 1991). Auditory and visual stimuli at attended locations elicit an enhanced negativity at midline electrodes as compared with stimuli at uncued locations. This effect consists of an initial peak (Nd1) around 160 ms that is usually maximal at posterior electrodes and is followed by a second, frontocentrally distributed negativity (Nd2) between 220 and 280 ms. Recent research (Eimer, 1996, 1997) has shown that these Nd effects are specific for transient attention situations. In addition, enhanced visual P1 and N1 components may also be observed for visual stimuli at cued locations, presumably indicating intraperceptual influences of visual spatial attention (Eimer, 1994; Luck et al., 1994; Mangun & Hillyard, 1991). The fact that the visual and auditory Nd1-Nd2 effects of spatial attention are highly similar and are affected in an analogous fashion by specific experimental manipulations (see Schröger & Eimer, 1997, for a more detailed discussion) may suggest that visual spatial and auditory spatial attention are not entirely modality specific but may at least partially depend upon common supramodal mechanisms. If spatial attention in audition and vision is not entirely modality specific, then there should be cross-modal links between visual spatial and auditory spatial attention. If so, directing attention to a specific location within one (relevant) modality should affect stimulus processing within the other (irrelevant) modality. This hypothesis will be further investigated in the present experiments.

The idea that there may be cross-modal links in spatial attention is supported by the everyday observation that attention will often be directed to sensory information stemming from different modalities but from the same location in space. 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 coordinated across modalities. Multisensory neurons found in several cortical and subcortical areas in the cat (Meredith & Stein, 1986) and primate (Morrell, 1972; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981) brain, including the superior colliculus (for an overview, see Stein & Meredith, 1993) a brain structure that is assumed to be involved in spatial attention (LaBerge, 1995), may play a role in the coordination of spatial attention across modalities.

Evidence in favor of a supramodal basis for spatial attention has been reported by Farah, Wong, Monheit, and Morrow (1989). These authors observed in parietal patients difficulties in disengaging attention from the ipsilesional hemispace in response to auditory and visual cues and argued that this difficulty may indicate the operation of a supramodal attentional system. Cross-modal links in exogenous (involuntary) spatial attention have recently been investigated by Spence and Driver (1997) in experiments where spatially uninformative cues (peripherally presented abrupt sounds or flashes) were presented prior to visual or auditory targets that required a location discrimination. Abrupt sounds attracted visual attention (reflected by more accurate visual discriminations on the cued side), whereas abrupt flashes apparently failed to attract auditory attention (discriminative performance with respect to auditory stimuli was independent of the position of the previously presented flash). On the basis of these results, Spence and Driver (1997) proposed the existence of asymmetrical links between audition and vision with respect to exogenous spatial attention. 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 (25% of all trials) and were somewhat more likely to be presented 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.

An ERP study that investigated cross-modal links between visual and auditory spatial attention was conducted by Hillyard, Simpson, Woods, Van Voorhis, and Münte (1984), who presented a stream of brief flashes and tone bursts at an eccentricity of 30° to the left or right of fixation. Separate groups of participants were instructed to attend to either the tones or the flashes and to press a button whenever a target (a tone or flash of slightly longer duration) was presented at the relevant location (left vs. right side), which was specified at the beginning of each block. For the participant group that attended to auditory stimuli, visual stimuli at attended locations elicited an enhanced negativity between 150 and 200 ms (N170), as compared with unattended locations. However, this effect was considerably larger for the participant group that attended to visual stimulus locations. Auditory spatial attention resulted in a broad negativity (Nd) elicited by stimuli at attended locations beyond 100 ms. This effect was also present, although somewhat smaller, when locations of visual stimuli were attended to. This pattern of results does not support the view that visual spatial attention and auditory spatial attention are completely separated, because ERP effects of spatial attention were found within one modality when the spatial attention was directed within the other modality. However, because these effects were considerably reduced when attention was directed to another modality spatial attention may not be entirely modality nonspecific.

In the ERP experiments reported here, a variation of the procedure adopted by Hillyard et al. (1984) was employed. ERPs elicited by visual and auditory stimuli were measured at attended and unattended locations when attention was directed to specific visual or auditory stimulus locations. Participants were required to respond to infrequently presented target stimuli of the attended modality whenever these stimuli were presented at the cued side and were required to ignore all stimuli of the unattended modality, all stimuli at uncued locations, and all nontargets. The attended modality (vision vs. audition) was specified in advance of each block. These manipulations permitted the simultaneous investigation of (a) ERP effects of intermodal attention by comparing the ERPs elicited by visual and auditory stimuli under conditions where these modalities were attended or unattended, (b) ERP effects of visual and auditory spatial attention by comparing the ERPs elicited by visual and auditory stimuli at cued and uncued locations when these modalities were attended, and (c) cross-modal links between visual and auditory spatial attention by comparing the visual and auditory ERPs to stimuli at cued and uncued locations when vision and audition were unattended.

Two attentional processes (attending to a modality: intermodal attention; attending to a location: spatial attention) were thus investigated. If intermodal attention were entirely modality specific, different ERP effects of intermodal attention should appear in the visual and the auditory modality (Woods et al., 1992). If intermodal attention were completely supramodal, very similar ERP effects should be present in the visual and auditory modality. If spatial attention were a modality-specific phenomenon, no evidence for cross-modal links between visual and auditory spatial attention (effects of spatial cueing on auditory ERPs when vision is attended and vice versa) should be obtained. If spatial attention were primarily based on supramodal mechanisms, ERP effects of spatial attention should be largely independent of which modality was attended. A third alternative is that spatial attention is neither completely supramodal nor entirely modality specific, but that attentional orienting within one stimulus modality has some (moderate) influence on processing within the other modality (Hillyard et al., 1984).

In contrast to the study of Hillyard et al. (1984), the relevant modality was varied within participants, and the to-be-attended location was not specified prior to each block (sustained attention) but was manipulated on a trial-by-trial basis with the help of centrally presented cues that signalled the relevant location for the next trial (transient attention). Because the mechanisms underlying sustained and transient spatial attention may not be entirely equivalent (Eimer, 1996), one question of the present research was whether cross-modal ERP effects of spatial attention similar to the results obtained by Hillyard et al. (1984) can be observed in a trial-by-trial cueing situation. In addition, cross-modal links in transient spatial attention were investigated because this situation can be more readily compared with recent behavioral studies (Spence & Driver, 1996, 1997) that also employed trial-by-trial cueing. Trial-by-trial cueing was employed because previous research has shown that highly similar ERP effects of spatial attention can be observed in the visual and auditory modality under transient attention conditions. In contrast to the intermodal attention study of Woods et al. (1992), visual and auditory stimuli were presented at nearby (Experiment 1) or identical (Experiment 2) locations, thereby reducing the possibility of confounding between intermodal and spatial attention.

EXPERIMENT 1

Methods

Participants

Fourteen paid volunteers participated in the experiment. Because 4 had to be excluded due to poor eye fixation control in the cue–target interval, 10 participants (6 women, 4 men), 21–38 years of age ($M = 30.9$ years) remained in the sample. All participants were right handed and had normal or corrected-to-normal vision.

Stimuli and Apparatus

Participants were seated in a dimly lit, electrically shielded and sound attenuated cabin with response buttons under their left and right hands. A computer screen was placed 110 cm in front of the participant's eyes and carefully positioned so that the visual stimuli (presented white on gray) appeared on the participant's horizontal straight-ahead line of sight. Two loudspeakers were attached to the left and right side of the computer screen (centered at a distance of about 9° from the screen center). Each trial began with a 200-ms presentation of a cue (an arrow pointing to the left or right side) that subtended a visual angle of $1.5° \times 0.6°$. Seven hundred milliseconds after the offset of the cue, an imperative stimulus was presented, either as a visual stimulus (an uppercase M or W, subtending an angle of $1° \times 1°$) or as an auditory stimulus (low-pitched or high-pitched sounds consisting of white noise band-pass filtered between 0 and 1000 Hz or between 1000 and 2000 Hz) that appeared for 100 ms. The visual stimuli were presented in the left or right hemifield at a horizontal distance of 6° from the screen center, and the auditory stimuli were delivered from the left or right loudspeaker. The interval between stimulus offset and the onset of the next cue was 2 s.

Procedure

Two experimental halves (attend vision and attend audition), each consisting of 12 blocks, were run successively, resulting in a total of 24 experimental blocks. Auditory and visual imperative stimuli appeared randomly and with equal probability on the cued side (valid trials) and on the uncued side (invalid trials). In the attend vision condition, participants were instructed to respond with a button press whenever the letter M (target stimulus) was presented at the cued side. In the attend audition condition, participants were instructed to respond with a button press whenever a high-pitched sound (target stimulus) was presented at the cued side. No response was to be executed to the letter M and the low-pitched sound (nontarget stimuli) at cued location and to all stimuli when they appeared at the uncued side. In half of the blocks, a left-hand response was required, and in the other half, a right-hand button press was required.

Each block consisted of 72 trials and had a duration of 3.6 min. A nontarget stimulus was presented on 48 trials. The probability of visual and auditory nontargets and of nontargets presented at the cued or uncued side and at the left or right side were equal, resulting in a total of six nontarget trials per block for each combination of condition (stimulus modality, trial validity, side of presentation). On the remaining 24 trials, a target stimulus was presented. These target trials were randomly drawn from a large sample where all combination of conditions (stimulus modality, trial validity, side of presentation) were equiprobable, so that on the average, three target trials were delivered per block for each of the eight possible combination of experimental conditions, out of which six trials (trials where a target of the relevant modality was presented at a cued location) required a response.

The order of the two experimental halves (attend vision and attend audition) was balanced across participants. Participants were instructed to respond as quickly and accurately as possible and to maintain central fixation during the trials. To make participants familiar with these specific task requirements, one training block was run at the beginning of the experiment.

Recording

The electroencephalogram (EEG) was recorded with Ag-AgCl electrodes from Fz, Cz, and Pz (according to the 10–20 system) 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 right earlobe. Horizontal electrooculogram (EOG) was recorded bipolarly from electrodes at the outer canthi of both eyes, and vertical EOG was recorded from electrodes above and below the right eye. Electrode impedance was kept below 5 kΩ. The amplifier bandpass was 0.1–40 Hz. EEG and EOG were sampled online every 5 ms and stored on disk. On each trial, a button press recorded within 1,000 ms after the onset of an imperative stimulus was considered as a response.

Data Analysis

EEG and EOG were epoched offline into periods of 1,700 ms, starting 100 ms prior to the onset of the cue and ending 700 ms after the onset of the imperative stimulus. Trials with eyeblinks, horizontal eye movements, or overt response errors were excluded from analysis. After artifact removal, the computer-averaged horizontal EOG for each participant was scored for systematic deviations of eye position in the cue–target interval. If the maximal residual EOG deviation exceeded $\pm 2\ \mu V$ (indicating a tendency to move the eyes in the direction of the arrow), the participant was disqualified. Only the EEG data obtained in nontarget trials were further analyzed. For each experimental condition, the total number of nontarget trials was 72, and the trial rejection rate was <30% for all participants and conditions. The EEG was averaged separately for all combinations of conditions (attended modality: attend audition vs. attend vision; stimulus modality: visual vs. auditory; trial validity: valid vs. invalid; visual field of presentation: left vs. right), resulting in 16 average waveforms for each participant and electrode site. All measures were taken relative to the mean voltage of the 100-ms interval preceding the onset of the imperative (nontarget) stimuli.

Effects of intermodal attention on the ERP waveforms were determined within two consecutive time windows (120–200 ms and 200–300 ms poststimulus). ERP effects of spatial attention were investigated within the following latency windows: visual P1 (90–120 ms poststimulus for contralateral occipital sites, 110–140 ms for ipsilateral occipital sites), visual N1 (160–200 ms for contralateral occipital sites, 170–210 ms for ipsilateral occipital sites), auditory N1 (100–140 ms at midline electrodes), Nd1 (160–210 ms at midline electrodes for visual and auditory stimuli), and Nd2 (220–280 ms at midline electrodes for visual and auditory stimuli). Mean amplitude values were obtained within these latency windows, and separate repeated measures analyses of variance (ANOVAs) were performed for visual and auditory stimuli and for lateral occipital and midline recording sites on these values for the following variables: attended modality (attend audition vs. attend vision), trial validity (valid vs. invalid), electrode location (Fz, Cz, Pz, for midline sites) or recording side (for lateral occipital electrodes), and stimulus location (left vs. right). Additional repeated measures ANOVAs were performed for single midline recording sites. When appropriate, a Greenhouse–Geisser adjustment to the degrees of freedom was performed, and the adjusted p values are reported. For the reaction time data, repeated-measures ANOVAs were performed for stimulus modality, spatial stimulus–response compatibility (compatible: stimulus and response side correspond; incompatible: stimulus and response are on opposite sides), and response side.

Results

Behavioral Performance

Responses tended to be faster for visual than for auditory target stimuli (442 ms vs. 479 ms), although this difference did not quite reach significance, $F(1,9) = 4.2$; $p < .07$. Spatial stimulus–response compatibility (454 ms vs. 467 ms for compatible and incompatible stimulus–response pairings, respectively) and response side (457 ms and 464 ms for right-hand and left-hand responses, respectively) had no significant effect on response latencies. Participants missed 3.4% of the auditory targets and 0.8% of the visual targets. False alarms occurred on <0.02% of all nontarget trials.

ERP Effects of Intermodal Attention

Figure 1 illustrates the effects of intermodal attention by comparing the ERPs elicited by auditory stimuli (left column) and visual stimuli (middle column) at midline electrodes and at occipital sites contralateral to the side of stimulus presentation (OC). The resulting relevant minus irrelevant modality difference waveforms for vision and audition are shown in Figure 1 (right column). Intermodal attention was reflected in a negative wave elicited by auditory and visual stimuli when the respective modality was attended. In audition, this effect showed a frontocentral distribution and was virtually absent occipitally. With visual stimuli, it was distributed more posteriorly.

No effect of attended modality on auditory ERPs was found at occipital sites. For auditory ERPs elicited at midline sites, a main effect of attended modality was present between 120 ms and 200 ms and between 200 ms and 300 ms, $Fs(1,9) > 13.7$, $ps < .01$. For the first latency window, an interaction between attended modality and electrode location was obtained, $F(2,18) = 9.0$, $p < .01$, $\epsilon = 0.85$. Although significant effects of attended modality were obtained at all three midline sites, additional paired t tests revealed that the effect was largest at Cz and larger at Fz than at Pz.

The difference between the attend vision and attend audition conditions affected the visual ERPs at occipital electrodes within both measurement windows, $Fs(1,9) > 6.0$, $ps < .05$. Between 120 ms and 200 ms, a three-way interaction was observed (Attended Modality × Recording Side × Stimulus Location), $F(1,9) = 5.8$, $p < .05$, reflecting the fact that the initial part of this effect was more pronounced at contralateral occipital sites. For visual ERPs elicited at midline sites, a main effect of attended modality was present between 120 ms and 200 ms and between 200 ms and 300 ms, $Fs(1,9) > 10.0$, $ps < .01$. Within both time windows, an interaction between attended modality and electrode location was observed, $Fs(2,18) > 5.6$, $ps < .05$, $\epsilon = 0.69$ and 0.88, respectively. Further analyses showed that between 120 ms and 200 ms, the effect was significant at Cz and Pz but was virtually absent at Fz (see Figure 1, right). Between 200 ms and 300 ms, significant effects of attended modality were present at Fz and Cz, whereas the effect only approached significance at Pz.[1]

[1] In the difference waveforms in Figure 1 (right), differential intermodal attention effects for vision and audition seem to be present within the first 100 ms after the onset of the imperative stimulus (particularly at Cz), with a negative-going deflection for audition and a positive-going deflection for vision. Because the intermodal attention effects in vision and audition were computed by subtracting ERPs obtained in the attend vision condition from ERPs obtained in the attend audition condition, and vice versa, any baseline difference between these conditions can be reflected in the initial part of the resulting difference waveforms. In fact, the later part of the contingent-negative variation measured in the cue–target interval was almost 1 μV larger in amplitude in the attend audition than in the attend vision condition, and this difference may have caused the early difference between audition and vision visible in Figure 1 (right).

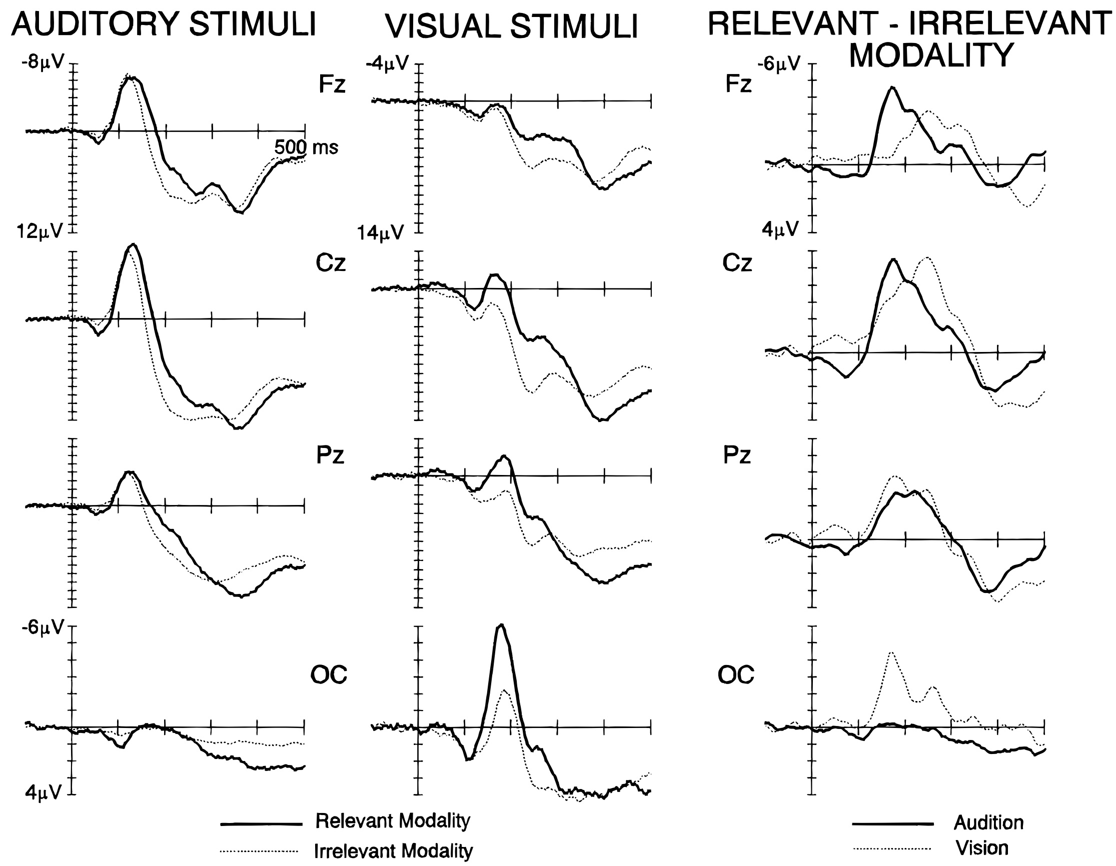

Figure 1. ERP effects of intermodal attention, Experiment 1. Grand-averaged ERPs elicited by auditory nontarget stimuli (left) and visual nontarget stimuli (middle) at midline electrodes and at occipital sites contralateral to the side of stimulus presentation (OC) when the respective modality was either relevant (thick lines) or irrelevant (thin dashed lines). Right: Difference waveforms for audition (thick lines) and vision (thin dashed lines) obtained by subtracting the ERPs elicited when the respective modality was irrelevant from the ERPs elicited when the modality was relevant.

ERP Effects of Spatial Attention Elicited by Auditory Stimuli

Figure 2 (left) shows the effects of spatial attention (valid vs. invalid trials) on auditory ERPs at midline electrodes when audition was attended or unattended. The resulting valid minus invalid difference waveforms are shown in Figure 3 (left). Spatial attention had an effect on auditory ERPs when audition was relevant, but no systematic ERP differences between valid and invalid trials were present when vision was relevant. Mean valid minus invalid difference amplitudes obtained in the Nd1 interval (at Pz) and the Nd2 interval (at Cz) under attend vision and attend audition conditions are displayed for both stimulus modalities in Figure 4 (left).

No effect of attention was observed for the auditory N1 component. Trial validity failed to reach significance in the Nd1 interval, $F(1,9) = 3.8$, $p < .09$, but a two-way interaction (Attended Modality $\times$ Trial Validity), $F(1,9) = 26.4$, $p < .001$, and a three-way interaction (Attended Modality $\times$ Trial Validity $\times$ Electrode Location), $F(2,18) = 9.1$, $p < .01$, $\epsilon = 0.64$, indicated that spatial attention affected the auditory ERPs differently in the attend audition and attend vision conditions. Additional analyses conducted separately for Fz, Cz, and Pz revealed that although the Nd1 validity effect was absent at Fz, it was significant at Pz and almost significant at Cz. At Cz and Pz, interactions between attended modality and trial validity were obtained. In the attend audition condition, significant effects of trial validity were present at Cz and at Pz, whereas no difference between valid and invalid trials was found for the attend vision condition (see Figure 3, left).

A similar pattern of results was observed in the Nd2 interval. An effect of trial validity, $F(1,9) = 31.5$, $p < .001$, was accompanied by an interaction between attended modality and trial validity, $F(1,9) = 14.9$, $p < .01$, and a three-way interaction (Attended Modality $\times$ Trial Validity $\times$ Electrode Location), $F(2,18) = 5.2$, $p < .05$, $\epsilon = 0.82$. Separate analyses conducted for Fz, Cz, and Pz revealed main effects of trial validity as well as Attended Modality $\times$ Trial Validity interactions at all three midline electrode sites. In the attend audition condition, effects of trial validity were present at all electrodes. In contrast, no such effects were present in the attend vision condition. This pattern of results can also be seen in the valid minus invalid difference waveforms of Figure 3 (left).

ERP Effects of Spatial Attention Elicited by Visual Stimuli

Effects of trial validity on the visual P1 and N1 components at contralateral and ipsilateral occipital sites are shown in Figure 4. No main effect of trial validity was found for the contralateral P1. However, an interaction between trial validity and attended modality was found, $F(1,9) = 5.6$, $p < .05$, reflecting the fact that an enlarged P1 was elicited by valid trials in the attend vision condition, $t(9) = 2.9$, $p < .05$, but not in the attend audition condition. A main effect of trial validity was found for the ipsilateral P1,

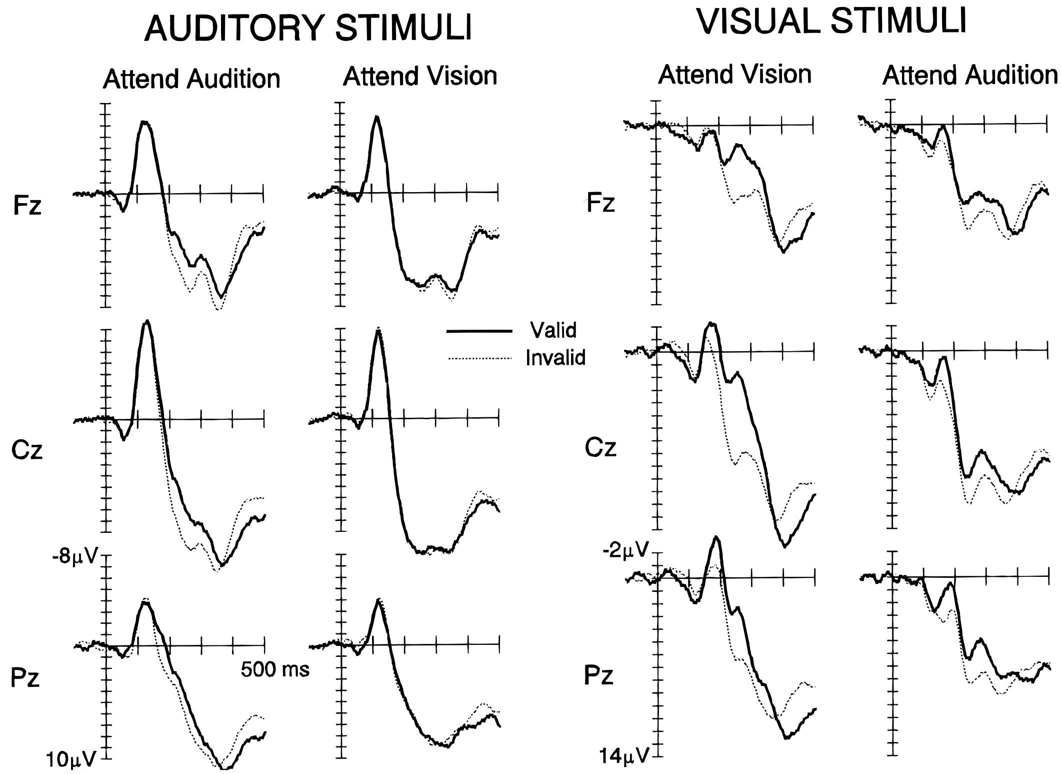

Figure 2. ERP effects of spatial attention, Experiment 1. Grand-averaged ERPs elicited by auditory stimuli (left) and visual stimuli (right) at midline electrodes in valid trials (thick lines) and invalid trials (thin dashed lines). Waveforms are displayed separately for the attend audition and attend vision conditions.

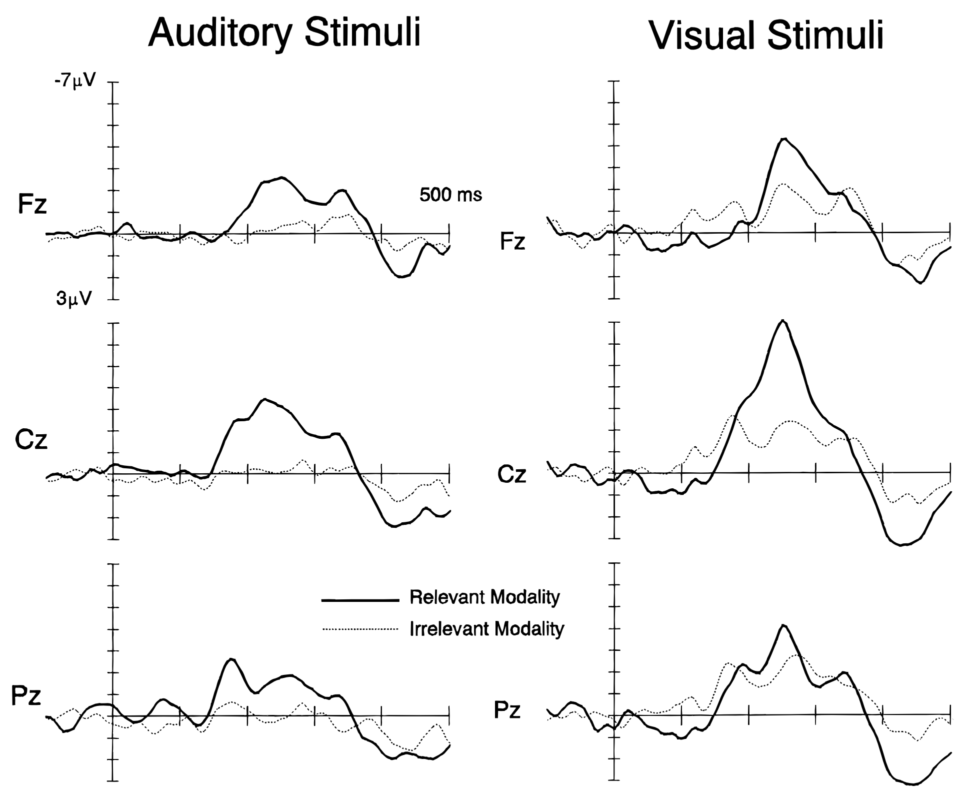

Figure 3. Difference waveforms obtained in Experiment 1 by subtracting auditory ERPs (left) or visual ERPs (right) elicited in invalid trials from the ERPs elicited in valid trials when the respective modality was relevant (thick lines) or irrelevant (thin dashed lines).

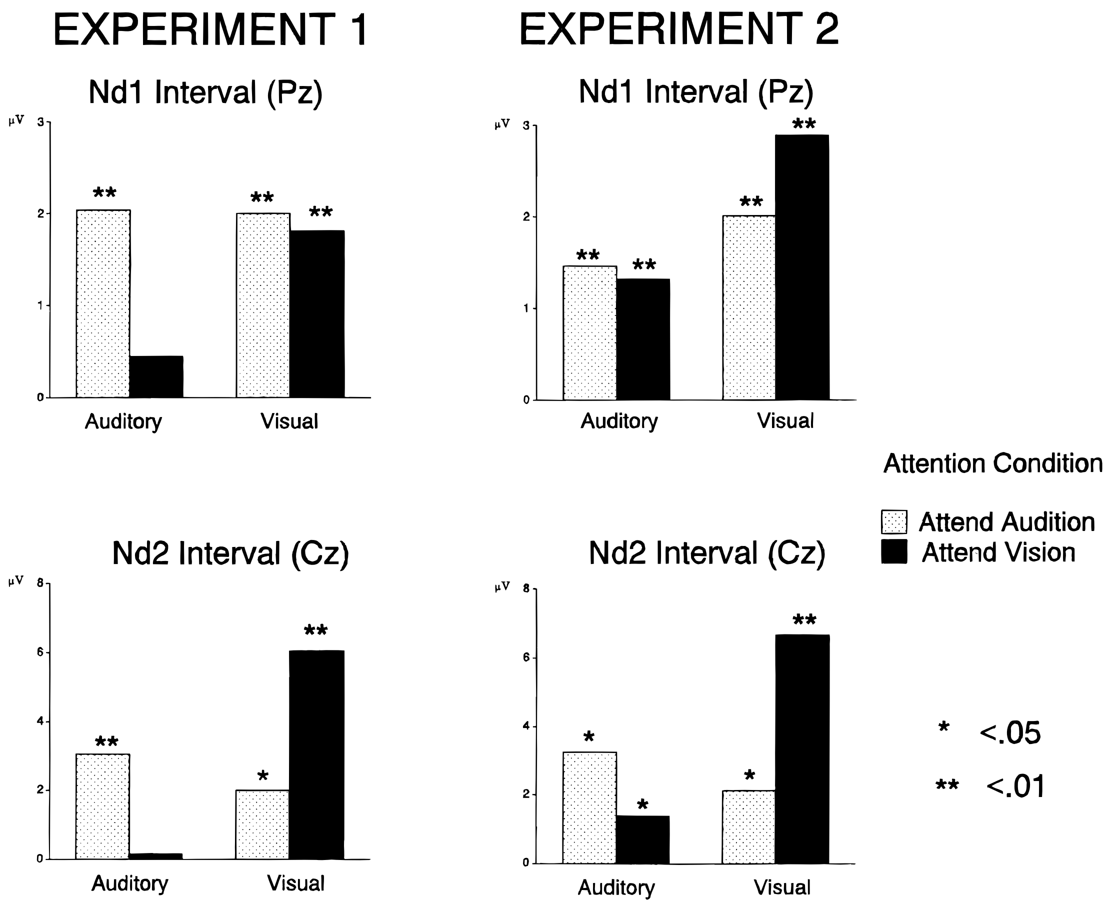

Figure 4. Mean valid minus invalid difference amplitude values obtained in Experiment 1 (left) and Experiment 2 (right) in the Nd1 interval (electrode Pz, top) and the Nd2 interval (electrode Cz, bottom) for visual and auditory stimuli in the attend audition and attend vision conditions. The significance levels of these differences are indicated (**$p < .01$; *$p < .05$).

$F(1,9) = 9.1$, $p < .05$. This effect was significant in the attend vision condition but failed to reach significance in the attend audition condition.

Trial validity affected the visual N1 at contralateral occipital sites, $F(1,9) = 7.1$, $p < .05$. The absence of any interaction between attended modality and trial validity indicated that this effect did not differ between the attend vision and attend audition conditions (see Figure 5, left). The contralateral N1 validity effect was only marginally significant in the attend vision condition but was significant for the attend audition condition. At ipsilateral occipital sites, trial validity had an almost significant effect, $F(1,9) = 5.0$, $p < .06$, which was accompanied by a Attended Modality × Trial Validity interaction, $F(1,9) = 5.7$, $p < .05$. A significant ipsilateral N1 validity effect was found for the attend vision condition but not for the attend audition condition.

In the Nd1 interval, an effect of trial validity, $F(1,9) = 35.5$, $p < .001$, was accompanied by an interaction between trial validity and electrode location, $F(2,18) = 12.3$, $p < .001$, $\epsilon = 0.77$. No interaction between attended modality and trial validity was obtained, indicating that trial validity affected the ERP waveforms similarly in the attend vision and attend audition conditions. Separate analyses conducted for electrodes Fz, Cz, and Pz revealed significant trial validity effects and Cz and Pz, without interactions between validity and attended modality. Additional *t* tests showed significant validity effects at these electrodes both in the attend vision condition and in the attend audition condition.

In the Nd2 interval, a main effect of trial validity, $F(1,9) = 20.5$, $p < .001$, was accompanied by an interaction between trial validity and electrode site, $F(2,18) = 5.8$, $p < .05$, $\epsilon = 0.94$, an Attended Modality × Trial Validity interaction, $F(1,9) = 26.4$, $p < .001$, and a three-way-interaction (Attended Modality × Trial Validity × Electrode Location) $F(2,18) = 9.1$, $p < .01$, $\epsilon = 0.64$. Significant effects of trial validity were found at all three midline electrodes. Interactions between attended modality and trial validity indicating larger Nd2 validity effects for the attend vision as compared with the attend audition condition were found at Fz and Cz but not at Pz (see also Figure 3, right). However, additional *t* tests revealed significant Nd2 validity effects for the attend vision and attend audition conditions at all three midline electrodes.

Discussion

In the present experiment, intermodal attention was manipulated by instructing participants to attend to one modality (vision or audition) and to ignore stimuli of the other modality. A comparison of the visual and auditory ERPs elicited when the respective modality was relevant or irrelevant revealed a broadly distributed negative wave for relevant-modality stimuli that started around 120 ms and extended up to 300 ms poststimulus (Figure 1). The scalp distribution of this intermodal attention effect was different in audition and in vision. For auditory ERPs, the effect was most

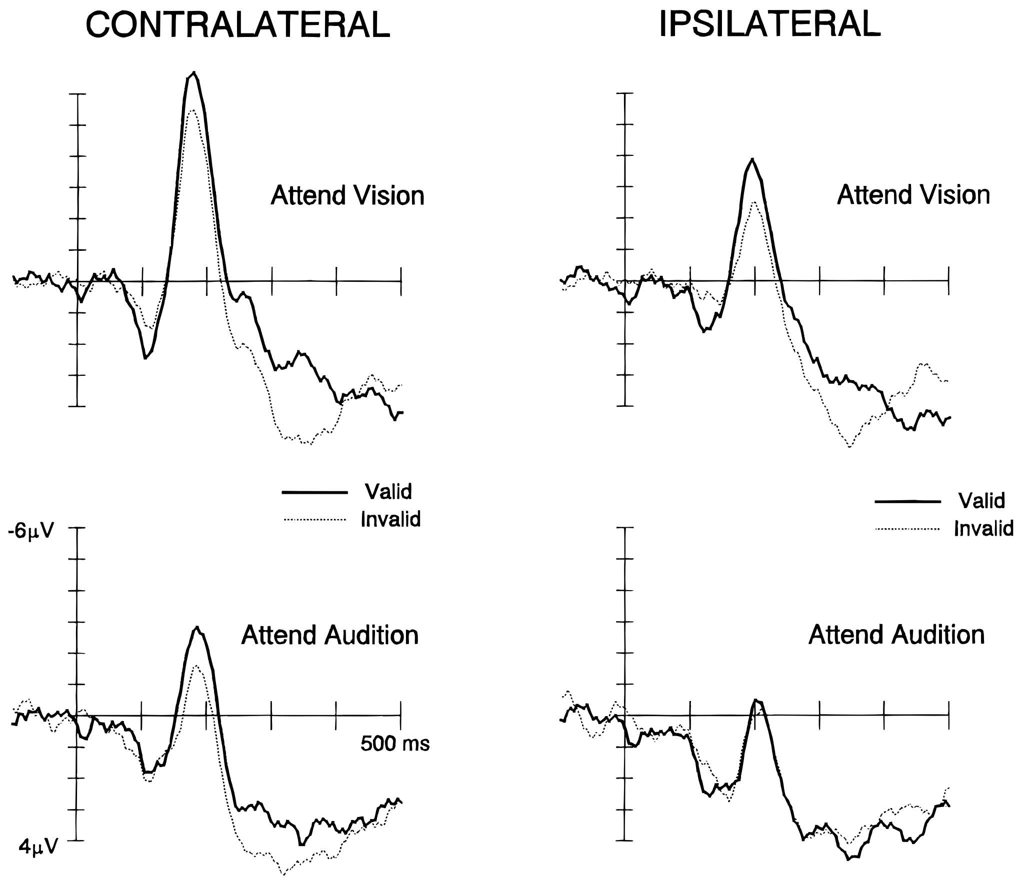

Figure 5. Grand-averaged ERPs elicited by visual stimuli at occipital sites contralateral and ipsilateral to the side of stimulus presentation in valid trials (thick lines) and invalid trials (thin dashed lines), Experiment 1. Waveforms are displayed separately for the attend vision and attend audition conditions.

pronounced at frontocentral sites and was completely absent at occipital electrodes (Figure 1, right). In the visual modality, the effect was initially absent at Fz but was clearly present at occipital electrodes (and was larger at sites contralateral to the visual field of stimulus presentation). This pattern of results is similar to the effects of intermodal attention reported by Woods et al. (1992), except for the fact that no enlarged positivity was observed when audition was relevant. The fact that differently distributed ERP effects of intermodal attention were obtained for vision and audition is consistent with the hypothesis that intermodal attention results in a selective modulation of processing within modality-specific brain areas.

The second issue to be investigated by the present experiment was whether the orienting of spatial attention within one (relevant) modality affects processing within the irrelevant modality, suggesting cross-modal links in spatial attention, or whether transient spatial attention operates separately within vision and audition. When vision was relevant, visual stimuli at cued locations elicited enhanced P1 and N1 components at occipital sites, presumably indicating an intraperceptual effect of visual spatial attention. Moreover, enhanced negativities for attended as compared with unattended locations were also observed in the Nd1 (at Cz and Pz) and Nd2 intervals at midline electrodes. A similar pattern of results was elicited by visual stimuli when audition was relevant. Again, enhanced negativities were elicited at midline electrodes by stimuli at cued locations in the Nd1 and Nd2 intervals. In the Nd1 interval, comparable effects of spatial attention were observed for visual ERPs in the attend vision and attend audition conditions. In the Nd2 interval, larger effects of spatial attention were observed at Fz and Cz when vision was relevant, although significant effects were also present when vision was irrelevant. These results are similar to those obtained within a sustained attention paradigm by Hillyard et al. (1984). In contrast to the attend vision condition, no attentional enhancements were present for the occipital P1 component in the attend audition condition. However, an enlarged N1 component elicited by visual stimuli at cued locations was found at contralateral occipital sites when vision was irrelevant.

A different pattern of results was obtained for auditory stimuli. When audition was relevant, significant attentional effects were found for the Nd1 interval (at Cz and Pz) and the Nd2 interval, reflecting enhanced negativities elicited by stimuli at cued locations as compared with stimuli at uncued locations. No such effects were found when vision was relevant, suggesting that visual spatial attention had no effect on the processing of auditory stimuli. Whereas the results obtained for visual stimuli strongly suggests cross-modal links in transient spatial attention, the pattern observed for auditory stimuli implies the existence of separate attentional subsystems within modalities. Taken together, these data seem to favor the assumption of asymmetrical links between vision and audition with respect to spatial attention, as postulated by Spence and Driver (1997) with respect to exogenous spatial attention: visual processing is influenced by auditory spatial attention, and auditory processing is independent from spatial orienting within the visual modality.

However, several issues must be considered before this conclusion is accepted. First, the results obtained for auditory stimuli contrast with the ERP results observed by Hillyard et al. (1984) and with the behavioral effects obtained by Spence and Driver (1996) that suggested symmetrical links between endogenous visual spatial and auditory spatial attention. This difference may be related to the specific spatial layout of the stimuli. Because auditory stimuli were delivered via loudspeakers that were attached to the computer screen, they were presented about 3° more eccentric than were the visual stimuli. If spatial attention was narrowly focused on the expected location of a relevant stimulus, stimuli of the irrelevant modality may well have been unattended, even though they were presented at the cued side. Although this scenario cannot readily explain why systematic effects of spatial attention were observed for visual stimuli in the attend audition condition, it does emphasize that the present experiment must be replicated under conditions where visual and auditory stimuli occupy identical locations in space before any conclusions with respect to asymmetrical links between vision and audition can be drawn. In Experiment 2, visual stimuli (light flashes) and auditory stimuli (tones) were presented under free-field conditions from lamps and loudspeakers located 15° to the left or right of fixation. Because only stimulus duration could be manipulated for the light flashes, duration discriminations were required to identify the visual and auditory target stimuli.

EXPERIMENT 2

Methods

Participants

Twelve paid volunteers participated in the experiment. Because 2 had to be excluded due to poor eye fixation control in the cue–target interval, 10 participants (7 women, 3 men), 22–38 years of age ($M = 28.8$ years) remained in the sample. All participants were right handed and had normal or corrected-to-normal vision.

Stimuli and Apparatus

Visual and auditory imperative stimuli were presented in the free field from pairs of lamps and loudspeakers on the left and right side, and the cue stimuli were presented on a computer screen. All stimuli were located at a distance of about 200 cm from the participant's eyes and were aligned on the participant's horizontal line of sight. The cues were presented at fixation, and the lamp–loudspeaker pairs were located 15° to the left or right of fixation. White noise (filter range: 100–10,000 Hz, 5 ms rise and fall time) of 100 ms and 150 ms duration served as auditory nontargets and targets, respectively. Visual nontarget and target stimuli were realized by flashing the lamp for 100 ms or 300 ms, respectively. The different durations for auditory and visual targets were chosen because pilot studies had shown that with these values, approximately equally difficult duration discriminations were realized in the visual and auditory modality. In all other respects, the experimental circumstances were identical to those of Experiment 1.

Procedure, Recording, and Data Analysis

The response instructions were different from those of Experiment 1. In the attend vision condition, participants were instructed to respond to a light stimulus of long duration (300 ms, visual target) whenever it appeared at the cued side. In the attend audition condition, participants were instructed to respond to a sound stimulus of long duration (150 ms, auditory target) whenever it appeared at the cued side. No response was to be given to short visual and auditory stimuli (100 ms duration) or to all stimuli when they appeared at uncued locations. In all other respects, the procedure, recording, and data analysis were identical to those of Experiment 1.

Results

Behavioral Performance

Response times to visual and auditory stimuli were not significantly different (600 ms vs. 592 ms). Spatial stimulus–response compatibility had an almost significant effect (588 ms vs. 605 ms for compatible and incompatible stimulus–response pairings, respectively), $F(1,9) = 4.98$, $p < .06$. All response latencies were measured relative to the onset of imperative stimli.[2] Participants missed 5.8% of the auditory targets and 2.6% of the visual targets. The false alarm rate on nontarget trials was <0.02%.

ERP Effects of Intermodal Attention

Figure 6 illustrates the effects of intermodal attention by comparing the ERPs elicited by auditory stimuli (left column) and visual stimuli (middle column) at midline electrodes and at contralateral occipital sites. The effects of intermodal attention on auditory and visual ERPs were very similar to the effects observed in Experiment 1.

No effect of attended modality on auditory ERPs was found at occipital sites. For auditory ERPs elicited at midline sites, main effects of attended modality were present between 120 ms and 200 ms and between 200 ms and 300 ms, $Fs(1,9) > 13.3$, $ps < .01$. Interactions between attended modality and electrode location were obtained within both measurement windows, $Fs(2,18) > 4.56$, $ps < .05$, $\epsilon = 0.83$ and 0.95, respectively. Although significant effects of attended modality were obtained in both latency windows and at all midline sites, additional paired *t* tests revealed that these effect were largest at Cz and tended to be smallest at Pz.

Intermodal attention affected the visual ERPs at occipital sites between 120 ms and 200 ms, $F(1,9) = 13.14$, $p < .006$, but not beyond 200 ms (see Figure 6, bottom). As in Experiment 1, a three-way interaction was observed between 120 ms and 200 ms (Attended Modality × Recording Side × Stimulus Location), $F(1,9) = 8.1$, $p < .05$, reflecting the fact that the effects of intermodal attention were more pronounced at contralateral occipital sites. At midline sites, main effects of attended modality on visual ERPs failed to reach significance within both measurement windows. However, there were interactions between attended modality and electrode location, $Fs(2,18) > 5.7$, $ps < .05$, $\epsilon = 0.96$ and 0.87, respectively. Further analyses showed that effects of attended modality were present at Cz within both time intervals but failed to reach significance at Fz and Pz.

ERP Effects of Spatial Attention Elicited by Auditory Stimuli

Figure 7 (left) shows the effects of spatial attention on auditory ERPs at midline electrodes when the respective modality was relevant or irrelevant, and the resulting valid minus invalid difference

[2]When making comparisons of the reaction times obtained in Experiment 2 with those of Experiment 1, it should be noted that the discrimination between longer duration targets and nontargets (100 ms duration) required in Experiment 2 had to await the expected offset of the nontargets.

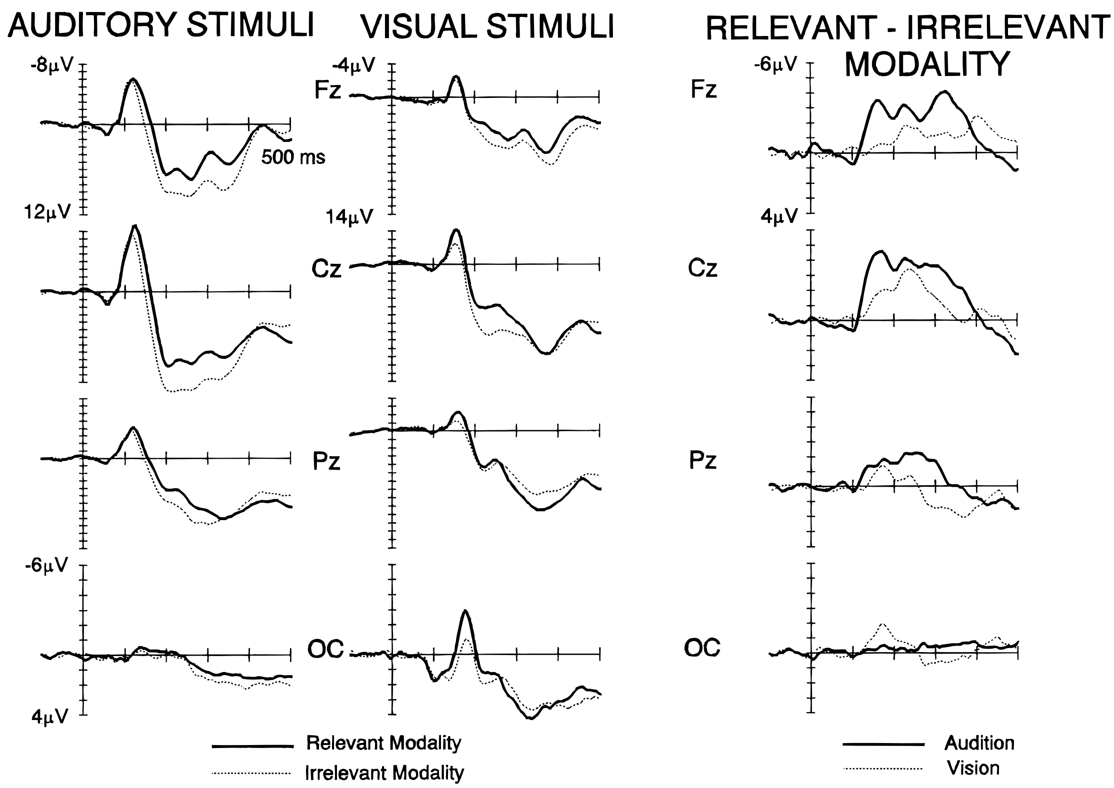

Figure 6. ERP effects of intermodal attention, Experiment 2. Grand-averaged ERPs elicited by auditory stimuli (left) and visual stimuli (middle) at midline electrodes and at occipital sites contralateral to the side of stimulus presentation (OC) when the respective modality was relevant (thick lines) or irrelevant (thin dashed lines). Right: Difference waveforms for audition (thick lines) and vision (thin dashed lines) obtained by subtracting the ERPs elicited when the respective modality was irrelevant from the ERPs elicited when the modality was relevant.

waveforms are shown in Figure 8 (left). In contrast to Experiment 1, ERP effects of spatial attention were visible also when audition was irrelevant (see also Figure 4, right).

No main effect of spatial attention was observed for the auditory N1 component. However, an enhanced auditory N1 for valid as compared with invalid trials was observed at Cz and Pz in the attend vision condition, *t*s $(9) > 2.8$, *p*s $< .05$ (see also Figure 7, left). In the Nd1 interval, trial validity had an effect, $F(1,9) = 19.1$, $p < .01$, and a two-way interaction (Trial Validity × Electrode Location), $F(2,18) = 7.5$, $p < .05$, $\epsilon = 0.63$, indicated that spatial attention affected the auditory ERPs differently at different sites. In contrast to Experiment 1, no Attended Modality × Trial Validity interaction was found for the Nd1 interval. Additional analyses conducted separately for Fz, Cz, and Pz revealed significant trial validity effects at Cz and Pz but not at Fz. No interactions between attended modality and trial validity were obtained, and additional *t* tests revealed significant trial validity effects at Cz and Pz in the attend audition condition and in the attend vision condition (see Figure 4, right, and Figure 8, left).

A similar pattern of results was observed in the Nd2 interval. A main effect of trial validity, $F(1,9) = 7.6$, $p < .05$, was accompanied by an interaction between trial validity and electrode location, $F(2,18) = 7.1$, $p < .01$, $\epsilon = 0.84$. As before (and in contrast to Experiment 1), the interaction between attended modality and trial validity failed to reach significance. However, an additional three-way interaction (Attended Modality × Trial Validity × Electrode Location), $F(2,18) = 5.9$, $p < .05$, $\epsilon = 0.58$, indicated that a differential effect of trial validity for the attend audition and attend vision conditions in the Nd2 interval was present at specific recording sites. Separate analyses conducted for Fz, Cz, and Pz confirmed this assumption: Significant main effects of trial validity were found at Fz and Cz but not at Pz, and a significant interaction between attended modality and trial validity was present at Cz. Additional *t* tests conducted separately for the attend audition and the attend vision conditions revealed significant effects of trial validity at Fz and Cz but not at Pz for both conditions (see also the valid minus invalid difference waveforms in Figure 8, left, and the bar graphs in Figure 4, right).

ERP Effects of Spatial Attention Elicited by Visual Stimuli

Effects of trial validity on the P1 and N1 components at contralateral and ipsilateral occipital sites are shown in Figure 9. No effects were found for the P1 at contralateral and ipsilateral occipital sites. At contralateral sites, trial validity had a significant effect on N1 amplitude, $F(1,9) = 8.2$, $p < .05$. The contralateral N1 validity effect was significant in the attend vision condition, $t(9) = 3.1$, $p < .05$, but failed to reach significance in the attend audition condition. At ipsilateral occipital sites, trial validity had a significant effect on N1 amplitude, $F(1,9) = 24.3$, $p < .001$, that was present both in the attend vision and the attend audition conditions.

In the Nd1 interval, a main effect of trial validity, $F(1,9) = 20.7$, $p < .001$, was accompanied by an interaction between trial validity and electrode location, $F(2,18) = 17.4$, $p < .001$, $\epsilon =$

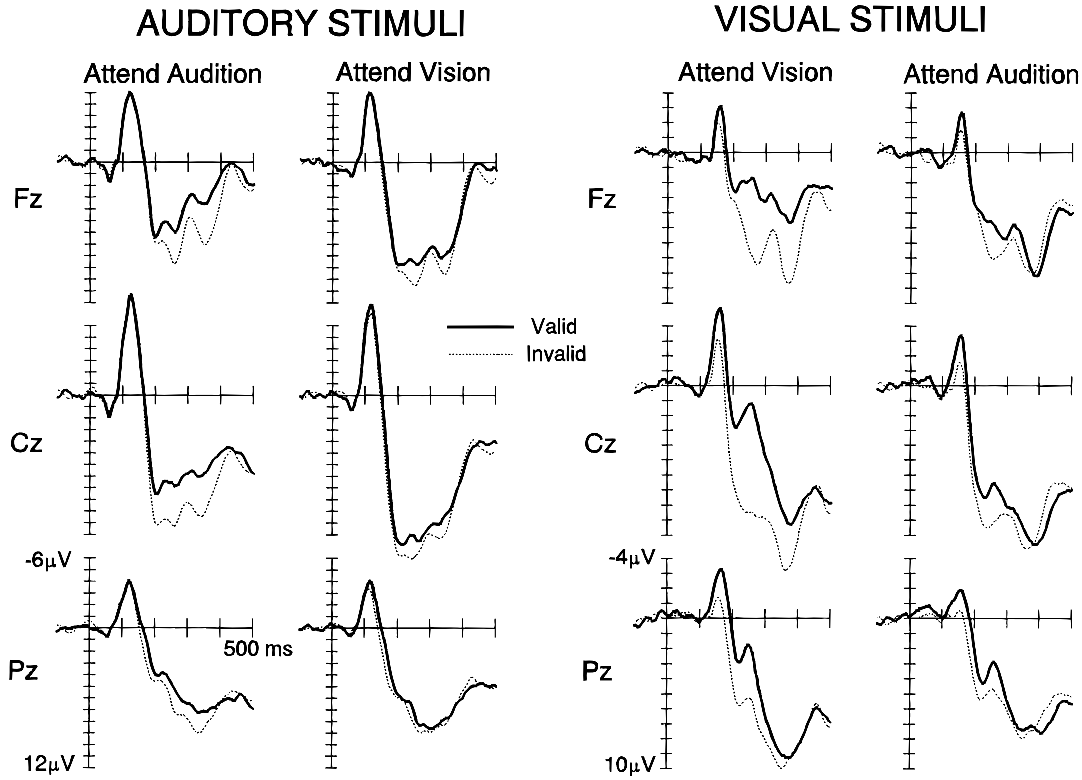

Figure 7. ERP effects of spatial attention, Experiment 2. Grand-averaged ERPs elicited by auditory stimuli (left) and visual stimuli (right) at midline electrodes in valid trials (thick lines) and invalid trials (thin dashed lines). Waveforms are displayed separately for the attend audition and attend vision conditions.

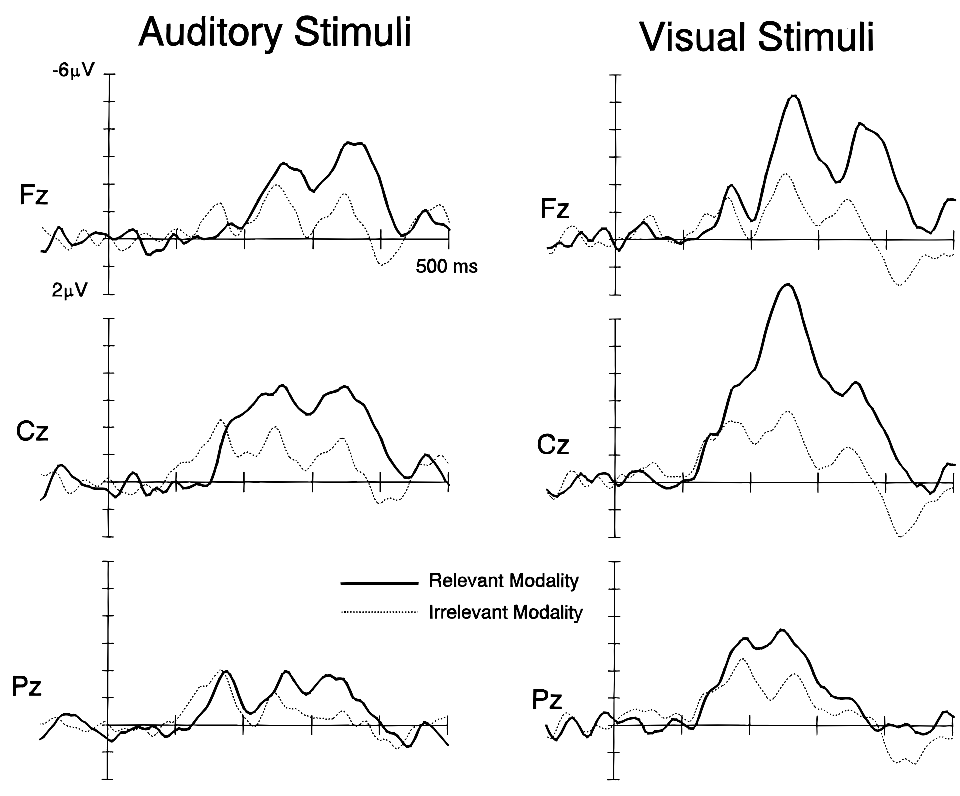

Figure 8. Difference waveforms obtained in Experiment 2 by subtracting auditory ERPs (left) or visual ERPs (right) elicited in invalid trials from the ERPs elicited in valid trials when the respective modality was relevant (thick lines) or irrelevant (thin dashed lines).

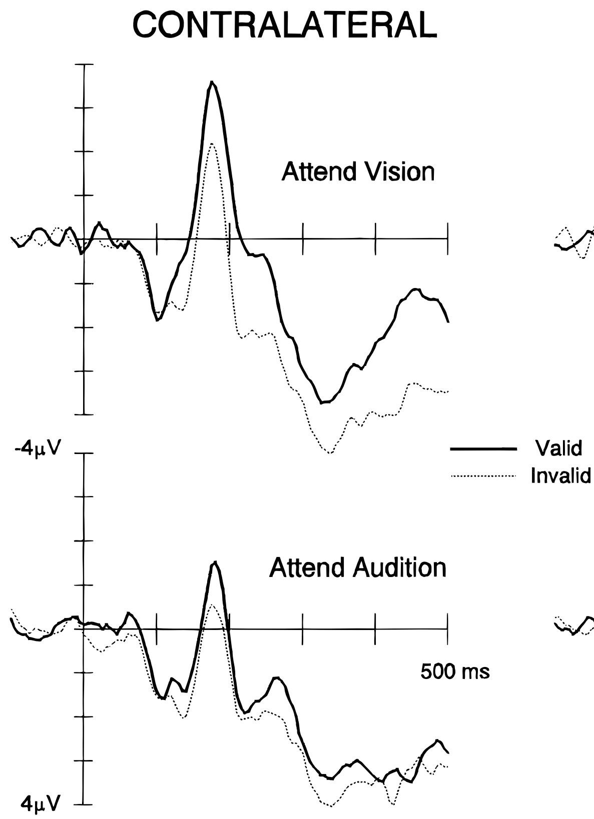

Figure 9. Grand-averaged ERPs elicited by visual stimuli at occipital sites contralateral and ipsilateral to the side of stimulus presentation in valid trials (thick lines) and invalid trials (thin dashed lines), Experiment 2. Waveforms are displayed separately for the attend vision and attend audition conditions.

0.85, and an interaction between attended modality and trial validity, $F(1,9) = 7.2$, $p < .05$. Separate analyses conducted for electrodes Fz, Cz, and Pz revealed significant trial validity effects at Cz and Pz but not at Fz and an interaction between trial validity and attended modality at Cz (see also Figures 7 and 8, right). Additional *t* tests showed significant validity effects at Cz and Pz in both the attend vision and attend audition conditions.

In the Nd2 interval, a main effect of trial validity, $F(1,9) = 19.7$, $p < .01$, was accompanied by an interaction between trial validity and electrode site, $F(2,18) = 10.2$, $p < .001$, $\epsilon = 0.99$, an Attended Modality × Trial Validity interaction, $F(1,9) = 5.7$, $p < .05$, and a three-way-interaction (Attended Modality × Trial Validity × Electrode Location), $F(2,18) = 9.9$, $p < .01$, $\epsilon = 0.73$. Significant effects of trial validity were found at all three midline electrodes. Significant Attended Modality × Trial Validity interactions indicating larger Nd2 validity effects for the attend vision than for the attend audition condition were found at Fz and Cz but not at Pz (see also Figure 8, right). Additional *t* tests revealed significant Nd2 validity effects for both the attend vision and attend audition conditions at all three midline electrodes.

Discussion

The effects of intermodal attention obtained in Experiment 2 were similar to the effects already observed in the first experiment. In audition, intermodal attention was reflected in a frontocentrally distributed negativity that was absent at occipital sites. However, the effects of intermodal attention on visual ERPs were somewhat smaller than in Experiment 1. Again, occipital effects of intermodal attention were larger at contralateral recording sites. The effects of spatial attention obtained for visual stimuli also confirmed the effects observed in Experiment 1: Visual stimuli at cued locations elicited an enhanced negativity in the Nd1 interval (at Cz and Pz) and in the Nd2 interval when vision was relevant but also in the attend audition condition. However, interactions between attended modality and trial validity obtained at Cz (in the Nd1 and Nd2 interval) and Fz (in the Nd2 interval) indicated larger attentional effects when vision was relevant. Spatial attention also enhanced occipital N1 amplitude. In the attend audition condition, this effect was significant only at ipsilateral sites. In contrast to Experiment 1, no attentional modulation was found for the visual P1, presumably because of the different visual discrimination tasks in the two experiments (letter discrimination vs. duration discrimination). The occipital P1 amplitude modulations caused by visual spatial attention are related to the type of sensory discrimination required in a given task (Eimer, 1993).

As in Experiment 1, enhanced negativities were elicited by auditory stimuli at cued locations in the Nd1 interval (at Cz and Pz) and the Nd2 interval (at Fz and Cz) when audition was relevant. In contrast to the first experiment, however, similar effects were also observed when vision was the relevant modality. In the Nd1 interval, similar effects of spatial attention on auditory ERPs were observed in both the attend audition and attend vision conditions. In the Nd2 interval, larger attentional effects were measured for the attend audition condition only at Cz, and effects of spatial attention were obtained at frontocentral sites when vision was relevant. In addition, an effect of spatial attention on the auditory N1 was found (at Cz and Pz) in the attend vision condition but not in the attend audition condition.

The processing of auditory stimuli was affected by attentional orienting within the visual modality and visual ERPs were affected by auditory spatial attention suggesting the existence of symmetrical links between vision and audition in transient spatial attention. Therefore, the results from Experiment 2 support the conclusions drawn by Spence and Driver (1996) on the basis of behavioral performance.

The overall reaction time was delayed by >100 ms as compared with Experiment 1 because the duration discrimination had to await the offset of the (shorter) nontarget stimuli. Despite this clear difference in the timing of response-related processing between both experiments, the onset and time course of the ERP effects of intermodal and spatial attention were highly similar. Our conclusion is that the attentional processes as reflected by the ERP modulations observed in the present research are largely independent of the timing of executive processes.

GENERAL DISCUSSION

We investigated whether two different attentional processes (intermodal attention: attending to a specific modality; spatial attention: attending to a specific location) are subserved by supramodal mechanisms or are largely modality specific. With respect to intermodal attention, the results of both experiments confirm the hypothesis originally based on the results reported by Woods et al. (1992): The scalp distribution of the intermodal attention effects in the auditory and visual modality was different, suggesting that attending to a stimulus modality primarily results in selective modulations of activity within modality-specific brain areas. One difference between the present results and the results described by Woods et al. (1992) is that no enhanced positivity was elicited by relevant auditory stimuli. According to Woods et al. (1992), this positivity might reflect the rejection of relevant standard (nontarget) auditory stimuli from further processing. One obvious difference between the present experiment and the Woods et al. (1992) study is that the interval between successive imperative stimuli was considerably larger (2,900 ms vs. 200–400 ms). Thus, differences in processing load related to these different interstimulus intervals may be responsible for the absence of this effect (see Alho et al., 1992, for effects of processing load on intermodal attention).

With respect to cross-modal links in transient spatial attention between vision and audition, a notable difference was obtained between Experiments 1 and 2: Whereas the data of Experiment 1 seemed to favor the hypothesis of an asymmetrical link between visual and auditory spatial attention, the ERP effects obtained in Experiment 2 suggest a symmetrical connection. Why were the auditory ERPs obtained in the attend vision condition affected by spatial attention in Experiment 2 but not in Experiment 1? One difference between the two experimental situations was that visual and auditory stimuli were delivered at identical locations in experiment 2, whereas in Experiment 1, auditory stimuli were delivered from more eccentric positions than were visual stimuli. The assumption that all irrelevant-modality stimuli at cued locations were simply unattended in Experiment 1 because of the horizontal separation of visual and auditory stimulus locations is not compatible with the fact that the attentional modulations of visual ERPs observed when audition was relevant were very similar in both experiments. One may assume that auditory spatial attention was generally less focused than visual spatial attention in the present study, so that in Experiment 1, the processing of visual stimuli at cued locations profited from auditory attention being shifted to that side, but not vice versa. Alternatively, visual processing was affected by auditory spatial attention in Experiment 1 perhaps because visual stimuli were presented centrally relative to the attended location when audition was relevant, whereas in the attend vision condition, auditory stimuli were located peripherally to the attended location. If the relative eccentricity of a stimulus with respect to the attended location were the critical variable for cross-modal effects of spatial attention to occur, one would predict attentional effects on auditory processing would be expected when vision was relevant, but not vice versa, whenever visual stimuli are presented more peripherally than are auditory stimuli. A possible reason for an effect of relative stimulus eccentricity on cross-modal links in spatial attention is that the size of the attentional focus varies with the retinal eccentricity of an attended location (Downing & Pinker, 1985). The focus of attention may thus be more restricted at 6° than at 9° and may thus have been even broader in Experiment 2, where all stimuli were presented at an eccentricity of 15°. These issues should be investigated in future experiments.

Based on the results of the present research, one may want to conclude that intermodal attention to audition and to vision is a modality specific phenomenon, whereas spatial attention is at least partially controlled by supramodal mechanisms. However, some issues must be considered with respect to these conclusions. In the present experiments, intermodal attention was varied between blocks, whereas spatial attention was varied between trials. Sustained and transient attention may not be completely equivalent with respect to the underlying brain mechanisms (Eimer, 1996). Therefore, the differences observed in the present research between transient spatial attention and sustained intermodal attention may be due, at least in part, to the different dynamics in allocating and shifting attention to stimulus modalities and to stimulus positions. In addition, in contrast to the Hillyard et al. (1984) study, the attend vision and attend audition conditions were varied within participants. As a result of this procedure, participants may not have directed their attention exclusively to the relevant stimulus modality but may have divided attention to some extent between both modalities. If so, the effects of spatial attention observed for the irrelevant modalities cannot be unambiguously interpreted as evidence for the existence of cross-modal links in spatial attention. The systematic effects of intermodal attention observed in the present experiment were similar to previous results reported by Woods et al. (1992), which seems to speak against such a divided attention mode. To further test these possibilities, effects of intermodal attention and cross-modal links in spatial attention must be investigated under conditions where intermodal and spatial attention are both manipulated in a sustained or transient fashion and relevant stimulus modalities are varied between participants. In addition, only a few electrodes were used in the present research, and more dense arrays may be needed to detect subtle differences in the effects of intermodal and spatial attention on visual and auditory ERPs.

The different scalp distributions observed for the intermodal attention effects in vision and audition were taken as evidence for the assumption that attending to a modality results in selective modulations of activities within modality-specific brain areas. However, these results do not rule out the possibility that such modality-specific modulations are themselves initiated by a single supramodal attentional control system, which could be located within polymodal areas of the parietal cortex. Conversely, the evidence for the existence of cross-modal links in spatial attention found at midline electrode sites does not rule out the possibility that spatial attention also has effects on modality-specific perceptual processing. In fact, visual spatial attention affected the amplitudes of visual evoked P1 and N1 components at occipital sites, whereas no such occipital components were elicited in response to auditory stimuli. It is important to distinguish between the activity of attentional control mechanisms and the resulting effects of attention in brain pathways and to realize that the control and the expression of attentional processes (LaBerge, 1995) may both have supramodal and modality-specific aspects.[3]

With these reservations in mind, we conclude from the present research that there are links between transient spatial attention in vision and in audition. The finding that orienting attention within one modality has consequences for the processing of stimuli within another modality shows that spatial attention is not entirely modality specific. However, the fact that larger Nd effects of spatial attention were obtained at midline sites when the respective modality was relevant than when it was irrelevant is not consistent with a model of a single supramodal control system of spatial attention that operates entirely independent of target modality (Farah et al. 1989) because this model would imply that the ERP effects of spatial attention reflecting the activity of this control system should be the same regardless of whether vision or audition was relevant. Because this sort of independence was not observed, it appears that transient spatial attention is neither completely supramodal nor entirely modality specific but that strong cross-modal links exist between visual and auditory spatial attention. Researchers will have to investigate in more detail the nature of these cross-modal links, including questions of whether cross-modal effects of spatial attention are modulated by differential processing requirements within the relevant modality and whether it is possible (despite the existence of cross-modal links) to simultaneously direct attention to different locations within different modalities.

[3]We thank Steve Luck for his clarifying comments with respect to this important distinction.

REFERENCES

Alho, K., Woods, D. L., Algazi, A., & Näätänen, R. (1992). Intermodal selective attention. II. Effects of attentional load on processing of auditory and visual stimuli in central space. *Electroencephalography and Clinical Neurophysiology*, *82*, 356–368.

Alho, K., Woods, D. L., & Algazi, A. (1994). Processing of auditory stimuli during auditory and visual attention as revealed by event-related potentials. *Psychophysiology*, *31*, 469–479.

Bédard, M. A., El Massioui, F., Pillon, B., & Nandrino, J. L. (1993). Time for reorienting of attention: A premotor hypothesis of the underlying mechanism. *Neuropsychologia*, *31*, 241–249.

Buchtel, H. A., & Butter, C. M. (1988). Spatial attention shifts: Implications for the role of polysensory mechanisms. *Neuropsychologia*, *26*, 499–509.

Downing, C. J. (1988). Expectancy and visual-spatial attention: Effects on perceptual quality. *Journal of Experimental Psychology: Human Perception and Performance*, *14*, 188–202.

Downing, C. J., & Pinker, S. (1985). The spatial structure of visual attention. In M.I. Posner & O.S. Marin (Eds.), *Attention and performance* (Vol. 11, pp. 171–187). Hillsdale, NJ: Erlbaum.

Eimer, M. (1993). Spatial cueing, sensory gating and selective response preparation: An ERP study on visuo-spatial orienting. *Electroencephalography and Clinical Neurophysiology*, *88*, 408–420.

Eimer, M. (1994). "Sensory gating" as a mechanism for visual-spatial orienting: Electrophysiological evidence from trial-by-trial cueing experiments. *Perception and Psychophysics*, *55*, 667–675.

Eimer, M. (1996). ERP modulations indicate the selective processing of visual stimuli as a result of transient and sustained spatial attention. *Psychophysiology*, *33*, 13–21.

Eimer, M. (1997). Attentional selection and attentional gradients: An alternative method for studying transient visual-spatial attention. *Psychophysiology*, *34*, 365–376.

Farah, M. J., Wong, A. B., Monheit, M. A., & Morrow, L. A. (1989). Parietal lobe mechanisms of spatial attention: Modality-specific or supramodal? *Neuropsychologia*, *27*, 461–470.

Hillyard, S. A., Simpson, G. V., Woods, D. L., Van Voorhis, S., & Münte, T. F. (1984). Event-related brain potentials and selective attention to different modalities. In F. Reinoso-Suarez & C. Ajmone-Marsan (Eds.), *Cortical integration* (pp. 395–414). New York: Raven Press.

LaBerge, D. (1995). *Attentional processing*. Cambridge, MA: Harvard University Press.

Luck, S. J., Hillyard, S. A., Mouloua, M., Woldorff, M. G., Clark, V. P., & Hawkins, H. L. (1994). Effects of spatial cuing on luminance detectability: Psychophysical and electrophysiological evidence for early selection. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 887–904.

Mangun, G. R., & Hillyard, S. A. (1991). Modulations of sensory-evoked brain potentials indicate changes in perceptual processing during visual-spatial priming. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 1057–1074.

Meredith, M. A., & Stein, B. E. (1986). Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. *Journal of Neurophysiology*, *56*, 640–662.

Morrell, F. (1972). Visual system's view of acoustic space. *Nature*, *238*, 44–46.

Müller, H. J., & Rabbitt, P. M. A. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 315–330.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In Pick, H. L., & Saltzman, E. J. (Eds.), *Modes of perceiving and processing information* (pp. 137–157). Hillsdale, NJ: Erlbaum.

Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *109*, 160–174.

Quinlan, P. T., & Bailey, P. J. (1995). An examination of attentional control in the auditory modality: Further evidence for auditory orienting. *Perception and Psychophysics*, *57*, 614–628.

Rizzolatti, G., Scandolara, C., Matelli, M., & Gentilucci, M. (1981). Afferent properties of periarcuate neurons in macaque monkeys: II. Visual responses. *Behavioral Brain Research*, *2*, 147–163.

Robin, D. A., & Rizzo, M. (1992). Orienting attention in audition and between audition and vision: Young and elderly subjects. *Journal of Speech and Hearing Research*, *35*, 701–707.

Schröger, E. (1993). Event-related potentials to auditory stimuli following transient shifts of spatial attention in a go/nogo task. *Biological Psychology*, *36*, 183–207.

Schröger, E. (1994). Human brain potential signs of selection by location and frequency in an auditory transient attention situation. *Neuroscience Letters*, *173*, 163–166.

Schröger, E., & Eimer, M. (1993). Effects of transient spatial attention on auditory event-related potentials. *Neuroreport*, *4*, 588–590.

Schröger, E., & Eimer, M. (1997). Endogenous covert spatial orienting in audition: "Cost-benefit" analyses of reaction times and event-related potentials. *Quarterly Journal of Experimental Psychology*, *50A*, 457–474.

Spence, C. J., & Driver, J. (1994). Covert spatial orienting in audition: Exogenous and endogenous mechanisms. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 555–574.

Spence, C. J., & Driver, J. (1996). Audiovisual links in endogenous covert spatial attention. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 1005–1030.

Spence, C. J., & Driver, J. (1997). Audiovisual links in exogenous covert spatial attention. *Perception and Psychophysics*, *59*, 1–22.

Spence, C. J., & Driver, J. (1992). On measuring selective attention to an expected sensory modality. *Perception and Psychophysics*, *59*, 389–403.

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. Cambridge, MA: MIT Press.

Woods, D. L., Alho, K., & Algazi, A. (1992). Intermodal selective attention: I. Effects on event-related potentials on lateralized auditory and visual stimuli. *Electroencephalography and Clinical Neurophysiology*, *82*, 341–355.

(Received June 5, 1997; Accepted November 5, 1997)