Psychophysiology, 37 (2000), 697–705. Cambridge University Press. Printed in the USA.

An event-related brain potential study of cross-modal links in spatial attention between vision and touch

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Abstract

Event-related potential (ERP) evidence for the existence of cross-modal links in endogenous spatial attention between vision and touch was obtained in an experiment where participants had to detect tactile or visual targets on the attended side and to ignore the irrelevant modality and stimuli on the unattended side. For visual ERPs, attentional modulations of occipital P1 and N1 components were present when attention was directed both within vision and within touch, indicating that links in spatial attention from touch to vision can affect early stages of visual processing. For somatosensory ERPs, attentional negativities starting around 140 ms poststimulus were present at midline and lateral central electrodes when touch was relevant. No attentional somatosensory ERP modulations were present when vision was relevant and tactile stimuli could be entirely ignored. However, in another task condition where responses were also required to infrequent tactile targets regardless of their location, visual-spatial attention modulated somatosensory ERPs. Unlike vision, touch apparently can be decoupled from attentional orienting within another modality unless it is potentially relevant.

Descriptors: Visual-spatial attention, Tactile-spatial attention, Cross-modal attention, Somatosensory event-related potentials, Event-related brain potentials

Research on spatial attention has traditionally focused on selective processing within single stimulus modalities. However, in recent years a growing number of studies have begun to study cross-modal links in endogenous (voluntary) and exogenous (involuntary) spatial attention (see Driver & Spence, 1998, for an overview). Most recent cross-modal studies have investigated links in spatial attention between vision and audition (e.g., Eimer & Schröger, 1998; Spence & Driver, 1996, 1997; Ward, 1994). For example, Spence and Driver (1996) measured behavioral performance in an elevation discrimination task, when a central arrow cue indicated the highly likely side of target stimuli for one modality. Target stimuli in the other modality were presented less frequently and were somewhat more likely to be presented at the uncued side. The results suggested symmetrical cross-modal links between endogenous spatial attention in audition and vision. When the central cue indicated the likely side of auditory targets, not only auditory discrimination but also visual discrimination became better for targets on the indicated side. Conversely, when visual targets were very likely on one side, auditory discrimination improved there as did visual discrimination.

Eimer and Schröger (1998) reported complementary evidence from event-related brain potentials (ERPs). They measured attentional modulation of visual and auditory ERPs when participants directed attention to the left or right within either audition or vision to detect infrequent targets within the relevant modality at that location. Attentional modulations of the occipital N1 component and an enhanced negativity at midline electrodes for stimuli at attended locations were found for visual ERPs when vision was relevant. Notably, these visual effects were also present, albeit attenuated, when attention was directed within audition, demonstrating cross-modal links. For auditory ERPs, spatial attention resulted in an enhanced negativity at midline electrodes when audition was relevant, and these effects remained present, albeit attenuated, when only vision was relevant (see also Hillyard, Simpson, Woods, Van Voorhis, & Münte, 1984, for similar results). These behavioral and ERP findings provide converging evidence for the existence of cross-modal links between vision and audition in endogenous spatial attention.

The aim of the present experiment was to use ERPs to test for cross-modal links in endogenous spatial attention between vision and touch. To date, only a few behavioral studies have investigated such links. Posner, Nissen, and Ogden (1978) measured choice response time (RT) to visual and tactile targets preceded by central precues that predicted the location of upcoming target stimuli with 80% validity but were uninformative with respect to target modality. RTs were faster for stimuli at cued locations, but error rates were also somewhat higher in these trials, suggesting possible criterion shifts for cued versus uncued locations. Moreover, be-

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This research has been supported by grants from the Medical Research Council and the Deutsche Forschungsgemeinschaft.

We thank Kate Parmenter, Steffan Kennett, and Friederike Schlaghecken for technical assistance.

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cause the central cues always predicted that visual and tactile targets were likely on a common side, attention may have shifted independently within each modality to the same place. Butter, Buchtel, and Santucci (1989) presented spatially informative peripheral visual or tactile precues prior to the onset of peripheral visual (Experiment 1) or tactile targets (Experiment 2) and found that targets were detected more quickly when they were presented at the cued side, regardless of cue modality. However, this finding does not provide unequivocal evidence for cross-modal links in spatial attention between vision and touch. Because the target modality was fixed and the peripheral precues were informative, this study may have induced an endogenous shift of spatial attention within just the relevant target modality, regardless of the modality of the cue (see Driver & Spence, 1994, for further discussion of this problem).

Spence, Pavani, and Driver (in press, Experiment 3) provided the first clear behavioral evidence for cross-modal links in endogenous spatial attention between vision and touch. Participants made an elevation discrimination in response to visual and tactile targets presented on the left or right side. In different blocks, one target modality was more likely than the other, and targets within this primary modality were highly likely to appear on one side, whereas targets of the secondary modality were somewhat more likely to be presented on the opposite side. Participants were instructed to direct their attention to the expected location of primary modality targets while leaving attention within the secondary modality diffuse. RTs were faster for stimuli presented on the side attended in the primary modality, both for the primary and secondary modality, regardless of whether touch or vision was primary, indicating a tendency for spatial attention to shift together in these modalities. However, attentional effects were larger for the primary modality, suggesting that spatial orienting within touch or vision affects processing for the other modality in an attenuated fashion, as previously found for audiovisual links in spatial attention (Eimer & Schröger, 1998; Spence & Driver, 1996).

If there are symmetrical cross-modal links in spatial attention between vision and touch, this linkage should be reflected in attentional ERP modulations comparable to the ERP effects observed in unimodal studies. For visual ERPs, spatial attention is known to result in amplitude modulations of occipital P1 and N1 components (Eason, 1981; Eimer, 1994; Mangun, Hillyard, & Luck, 1993) and in enhanced negativities for attended stimuli at midline electrodes (Eimer, 1996; Eimer & Schröger, 1998). Attentional P1 and N1 modulations are interpreted as evidence for perceptual sensory gating processes within visual perception (Mangun, 1995), whereas the later effects may primarily reflect attentional modulations of postperceptual processes (Eimer, 1998; Mangun & Hillyard, 1991). If there are cross-modal links in spatial attention from touch to vision, similar although perhaps attenuated effects on visual ERPs should be found when attention is directed to the location of tactile stimuli. Similar predictions can be made for somatosensory ERPs, although only relatively few researchers to date have investigated unimodal ERP effects of spatial attention in the somatosensory modality. Michie (1984) found enhanced negativities for tactile stimuli at attended locations that were largest at central electrodes contralateral to the stimulated side. The somatosensory N1 component (mean latency = 130–150 ms) was not affected by spatial attention, but attentional negativities overlapped with the subsequent P2 and N2 components. In other studies, researchers found attentional N1 modulations, with larger N1 components elicited by tactile stimuli at attended locations (García-Larrea, Lukaszewicz, & Mauguière, 1995; Michie, Bearpark, Crawford, & Glue, 1987). In García-Larrea et al.'s study, this effect tended to be earlier (around 120 ms poststimulus) over the hemisphere contralateral to the stimulation. Cross-modal links in spatial attention from vision to touch should be reflected in similar although possibly smaller attentional effects on somatosensory ERPs when attention is directed to the location of visual stimuli.

In a pilot study for the present experiment, ERPs were recorded in a situation where single tactile and visual stimuli were presented in random order on the left or right side. Attention had to be directed to the left or right within either vision or touch to detect infrequent targets of this relevant modality at the attended location. The currently irrelevant modality could be completely ignored. ERP evidence for the existence of cross-modal links from touch to vision was indeed found. When compared with unattended stimuli, visual stimuli at attended locations elicited larger occipital N1 components and an enhanced negativity at midline electrodes not only when vision was relevant but also when touch was relevant. However, a very different pattern of results was obtained for somatosensory ERPs. Although enlarged negativities for attended tactile stimuli were observed when touch was relevant, no attentional ERP modulations were elicited when vision was relevant and tactile stimuli could be ignored. These findings may suggest the existence of asymmetrical links in spatial attention between vision and touch, with vision being affected by tactile attention but not vice versa. An immediate problem for this interpretation was posed by Spence et al.'s (in press) behavioral demonstration of symmetrical cross-modal links between vision and touch. In their study, effects of tactile-spatial attention on visual discrimination were equivalent to the effects of visual-spatial attention on tactile discrimination latencies.

There is however a potentially important difference between the Spence et al. (in press) study and our ERP pilot experiment. To demonstrate effects of visual-spatial attention on tactile discrimination, Spence et al. obviously had to instruct participants to respond to visual as well as to tactile stimuli. In contrast, in our pilot study, where visual-spatial attention failed to affect somatosensory ERPs, none of the tactile stimuli required any response, that is, touch could be completely ignored when vision was relevant. The same applied for the visual-auditory study of Eimer and Schröger (1998), and yet cross-modal effects were apparent in the visual and auditory ERPs. Nevertheless, the possibility should be considered that tactile information processing is special in that tactile stimuli can be decoupled from spatial attention in other modalities when they can be completely ignored but not when they remain potentially relevant for responding. In contrast, cross-modal links in vision and audition may be present regardless of the response relevance of visual and auditory stimuli.

This hypothesis was put to test in the present experiment by comparing attentional modulations of visual and somatosensory ERPs in three different task conditions. Tactile and visual stimuli were presented randomly and with equal probability on the left or right side. Participants were instructed to attend to the left or right side for an entire experimental block and to respond to infrequent target stimuli. In the judge-vision condition, only visual targets at attended locations required a response and tactile stimuli could be entirely ignored. In the judge-touch condition, only tactile targets at attended locations required a response and visual stimuli could be entirely ignored. A third condition (vision-primary/touch-secondary) was identical to the judge-vision condition except that participants now also had to respond to rare target stimuli regardless of their location. Thus, although participants still had no reason to focus tactile attention on just the side that was relevant for vision, as for the judge-vision condition, they could no longer entirely ignore touch because they occasionally had to response to tactile targets on either side. To keep vision the primary modality and to ensure focused attention to just one side within vision, each block contained 12 visual targets at the attended location but only three tactile targets on the left side and three tactile targets on the right.

If there are cross-modal links in spatial attention from touch to vision, attentional modulations of visual ERPs in the judge-touch condition should be similar to the effects observed in the judge-vision condition. For somatosensory ERPs, attentional modulations were expected for the judge-touch condition.[1] If there were symmetrical cross-modal links between vision and touch, similar effects should be seen in the judge-vision condition. In contrast, no such effects of visual-spatial attention on somatosensory ERPs should be elicited if touch could be decoupled from attentional orienting within vision whenever tactile stimuli can be completely ignored. However, if touch cannot be decoupled from visual-spatial attention in this way when it remains potentially response relevant, as in the behavioral study of Spence et al. (in press), attentional effects on somatosensory ERPs should become apparent in the vision-primary/touch-secondary condition.

Methods

Participants

Fourteen paid volunteers participated in the experiment. One of them had to be excluded because of a large number of eye blinks during trials, and one was excluded because of excessive α wave activity. Thus, 12 participants (5 women), 22–39 years of age ($M =$ 26.5 years) remained in the sample. Ten participants were right-handed, two were left-handed, and all had normal or corrected-to-normal vision.

Stimuli and Apparatus

Participants sat in a dimly lit experimental chamber with a head-mounted microphone positioned about 2 cm in front of the mouth. Tactile stimuli were presented using two 12-volt solenoids that drove a metal rod with a blunt conical tip through a small hole onto the outside of the index fingers (see Spence, Nicholls, Gillespie, & Driver, 1998). The rods made contact with the pad of the participant's index finger whenever a current was passed through the solenoid. The rods and fingertips were occluded so that participants could not see any movements of the rods. White noise was presented from the central loudspeaker at 72.5 dB(A), as measured from the participant's head, throughout the experimental blocks to mask any sounds made by the operation of the tactile stimulators. Visual stimuli were presented by illuminating an ensemble of green LEDs consisting of six segments arranged in a circle plus one central segment. The angular size of each LED was 0.65°, and the diameter of the circle was 2.4°. A small black cross printed on paper and attached to the central loudspeaker at an angle of about 30° below eye level served as the fixation point. The two tactile stimulators and the two LED ensembles were placed on a table 25° to the left or right of the central fixation cross at a viewing distance of about 45 cm from the participant's eyes.

Tactile nontarget stimuli consisted of one rod tip contacting the participant's index finger for 200 ms. Tactile target stimuli had a gap, where this continuous contact was interrupted for 10 ms after a duration of 95 ms. Visual nontarget stimuli consisted of the continuous illumination of one LED ensemble for 200 ms. For visual target stimuli, which like the tactile targets included a gap, the LED ensemble was illuminated for 95 ms, turned off for 10 ms, and illuminated again for 95 ms. Vocal response onset times were measured with a voice key.

Procedure

The experiment consisted of 24 experimental blocks of 96 trials each, with an intertrial interval of 1,000 ms. In 72 trials, visual or tactile nontargets were presented with equal probability and in random order on the left or right side. In the remaining randomly intermingled 24 trials, visual and tactile stimuli with gaps were presented. Three task conditions were delivered, each consisting of eight successive blocks. In the judge-vision condition, the task was to respond vocally (by saying "yes") whenever a visual gap target was presented at the attended location (left or right). In the judge-touch condition, the task was to respond vocally whenever a tactile gap target was presented at the attended location (left or right). In these two conditions, 18 gap stimuli in the relevant modality (12 at the attended side that required a response and 6 at the unattended side) plus 6 gap stimuli in the irrelevant modality (3 left, 3 right) were delivered. In the vision-primary/touch-secondary condition, stimulus probabilities were identical to the judge-vision condition, as were the instructions except that participants now also had to respond whenever a tactile target was detected on either side. It was emphasised that tactile targets were infrequent and would appear with equal probability at the attended and unattended side. Each of the three task conditions consisted of four blocks where participants had to attend in the primary modality to the left side and four blocks where they attended to the right. These were presented in random order. The order in which the three task conditions were delivered was balanced across participants. Instructions specifying the task-relevant modality and the attended location were displayed on a computer screen prior to the start of each block.

Participants were instructed to respond as quickly and accurately as possible and to maintain central eye fixation throughout the blocks. Several training blocks were presented prior to the beginning of the first experimental block. Eye movements were closely monitored during these training blocks. Whenever the horizontal electrooculogram (EOG) revealed that participants did not maintain central eye fixation, they were reminded again of the necessity of continuously fixating on the central cross throughout an experimental block. Additional training blocks were presented until fixation control was regarded as satisfactory.

Recording and Data Analysis

The electroencephalogram (EEG) was recorded with Ag/AgCl electrodes and linked-earlobe reference from Fpz, Fz, Cz, Pz, C3, and C4 (according to the 10-20 system) and from OL and

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[1] In previous unimodal spatial attention studies, somatosensory ERPs were elicited by electrical stimulation of the fingertips, whereas tactile stimuli were delivered by punctators in the present study. Because the amplitudes and latencies of somatosensory ERP components depend on the type and intensity of tactile stimulation, previous results allow no clear prediction with respect to the exact latencies of attentional ERP effects. We expected to find enhanced negativities elicited by tactile stimuli at attended locations in the N1, P2, and N2 time range when touch was relevant. Therefore, two rather broad latency windows were defined for the analysis of somatosensory ERPs. The early time interval ranged from 140 ms to 200 ms poststimulus and was expected to overlap with the somatosensory N1, and the later time window, ranging from 200 ms to 280 ms poststimulus, was expected to include the P2 and N2 components.

OR (located halfway between O1 and T5, and O2 and T6, respectively). Horizontal EOG (HEOG) was recorded bipolarly from the outer canthi of both eyes. The impedance was kept below 10 kΩ for the EOG electrodes and below 5 kΩ for all other electrodes. The amplifier bandpass was 0.1–40 Hz. EEG and EOG were sampled with a digitization rate of 200 Hz and stored on disk. Vocal response onset times were measured for each response to detected gap targets.

EEG and EOG were epoched offline into 800-ms periods starting 100 ms prior to and ending 700 ms after the onset of the stimulus. Only EEG epochs obtained for nontarget trials were further analyzed, to avoid contamination by vocal responses. Trials with eyeblinks (Fpz exceeding $\pm 60\ \mu$V relative to 100-ms prestimulus baseline), horizontal eye movements (HEOG exceeding $\pm 30\ \mu$V relative to baseline), other artifacts (a voltage exceeding $\pm 60\ \mu$V at any electrode location relative to baseline), or vocal responses recorded on nontarget trials were excluded from analysis. The EEG to the nontarget stimuli was averaged separately for all combinations of stimulus modality (vision vs. touch), stimulus location (left vs. right), task (judge-vision vs. judge-touch vs. vision-primary/touch-secondary) and attended location (left vs. right), resulting in 24 ERP waveforms for each participant and electrode site. After averaging, HEOG waveforms were scored for any systematic deviations of eye position, indicating residual tendencies to move the eyes to the location of target stimuli. A residual EOG deviation exceeding $\pm 2\ \mu$V would lead to the disqualification of participants.

All ERP measures were taken relative to the mean voltage of the 100-ms prestimulus baseline interval, and all latencies are given relative to stimulus onset. Mean amplitude values were computed separately for visual and somatosensory ERPs within prespecified time windows. For visual ERPs, the following latency windows were used: P1, 90–130 ms for lateral occipital sites; N1, 160–210 ms for lateral occipital and midline sites; and Nd, 210–280 ms for lateral occipital and midline sites).[2] For somatosensory ERPs, two latency windows were analyzed separately for lateral central and midline electrodes: early Nd (Nde: 140–200 ms) and late Nd (Ndl: 200–280 ms). Separate repeated measures analyses of variance (ANOVAs) were performed on ERP mean amplitude values obtained at midline and at lateral recording sites for the variables task (judge-vision vs. judge-touch vs. vision-primary/touch-secondary), spatial attention (attended vs. unattended location), stimulus side (left vs. right), and electrode location (Fz vs. Cz vs. Pz for midline electrodes, left vs. right for lateral electrodes). Separate ANOVAs were also conducted for each task condition. When appropriate, Greenhouse-Geisser adjustments to the degrees of freedom were performed, and the adjusted *p* values are reported. One-tailed paired *t* tests were performed to investigate predicted spatial attention effects at single midline sites. Nonsignificant terms and results trivially due to stimulus and anatomical laterality are not reported. For the vocal responses, repeated measures ANOVAs were performed on response latencies for the variables task and stimulus side, and paired *t* tests were conducted on arcsine-transformed error rates.

Results

Behavioral Performance

Vocal RTs to visual target stimuli (measured relative to the onset of the target-defining gap) were 485 ms and 479 ms in the judge-vision and vision-primary/touch-secondary conditions. Response times to tactile targets were 448 ms and 544 ms in the judge-touch and vision-primary/touch-secondary conditions. Tactile RTs in the judge-touch condition were faster than visual RTs in the judge-vision condition, $F(1,11) = 6.85$, $p < .024$. Tactile responses were faster in the judge-touch condition than in the vision-primary/touch-secondary condition, $F(1,11) = 98.65$, $p < .001$. Importantly, responses to tactile targets in the vision-primary/touch-secondary condition were faster for stimuli presented at visually attended locations than for those presented at visually unattended locations (511 ms vs. 577 ms), $F(1,11) = 32.38$, $p < .001$, confirming the behavioral cross-modal link documented by Spence et al. (in press).

Participants missed visual targets in the judge-vision and vision-primary/touch-secondary conditions significantly more often (16.2% and 11.3%, respectively) than they missed tactile targets in the judge-touch condition (0.6%), both $t(11) > 4.6$, both $p < .001$. Participants missed 4% of all tactile targets in the vision-primary/touch-secondary condition, which was more than were missed in the judge-touch task, $t(11) = 3.39$, $p < .006$. More tactile targets were missed in the vision-primary/touch-secondary condition on the unattended side (6.6%) than on the attended side (1.4%), $t(11) = 2.31$, $p < .041$. The rate of false alarms to nontarget stimuli was 1%, 0.12%, and 1.4% in the judge-vision, judge-touch, and vision-primary/touch-secondary conditions, respectively.

Effects of Spatial Attention on Visual ERPs

Figure 1 (left half) shows ERPs elicited by visual stimuli at lateral occipital electrodes in the judge-vision, judge-touch, and vision-primary/touch-secondary conditions. Larger occipital P1 and N1 components were elicited by visual stimuli at attended locations in all three task conditions. This was reflected in main effects of spatial attention for P1 amplitudes, $F(1,11) = 17.16$, $p < .002$, and for N1 amplitudes, $F(1,11) = 9.86$, $p < .009$. No Spatial attention × Task interaction was obtained for P1 amplitudes, and subsequent ANOVAs conducted separately for each task revealed attentional P1 modulations for all three task conditions, all $F(1,11) > 5.3$, all $p < .042$. A Spatial attention × Task interaction was present for N1, $F(2,22) = 4.65$, $p < .029$, $\epsilon = 0.829$); attentional modulations for this component were largest in the judge-vision condition and smallest in the judge-touch condition (Figure 1, left half). However, separate follow-up ANOVAs showed significant attentional N1 effects for all three tasks, all $F(1,11) > 5.0$, all $p < .047$. No significant Spatial attention× Stimulus side × Electrode location interactions were present for P1 and N1 amplitudes, suggesting that effects of spatial attention were similar at contralateral and ipsilateral occipital electrodes (see Figure 1, left). In the Nd time range (210–280 ms poststimulus), a main effect of spatial attention at lateral occipital sites, $F(1,11) = 6.41$, $p < .028$, was accompanied by a highly significant Spatial attention × Task interaction, $F(2,22) = 13.98$, $p < .001$, $\epsilon = 0.855$. As can also be seen in Figure 1 (left side), enhanced negativities for attended as compared with unattended stimuli were present in the judge-vision and the vision-primary/touch-secondary conditions, both $F(1,11) > 7.7$, both $p < .02$, but not in the judge-touch condition (Figure 1, left half).

Figure 2 shows visual ERPs elicited in the three task conditions at midline electrodes together with the resulting attended minus

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[2] The term *Nd* is usually employed in the context of difference waveforms, where it refers to the negative difference obtained when subtracting ERPs to unattended stimuli from ERPs to attended stimuli, reflecting an enhanced negativity elicited by attended relative to unattended stimuli in the unsubtracted waveforms. We were expecting to obtain such attentional negativities within the Nd analysis intervals as defined for visual and somatosensory ERPs.

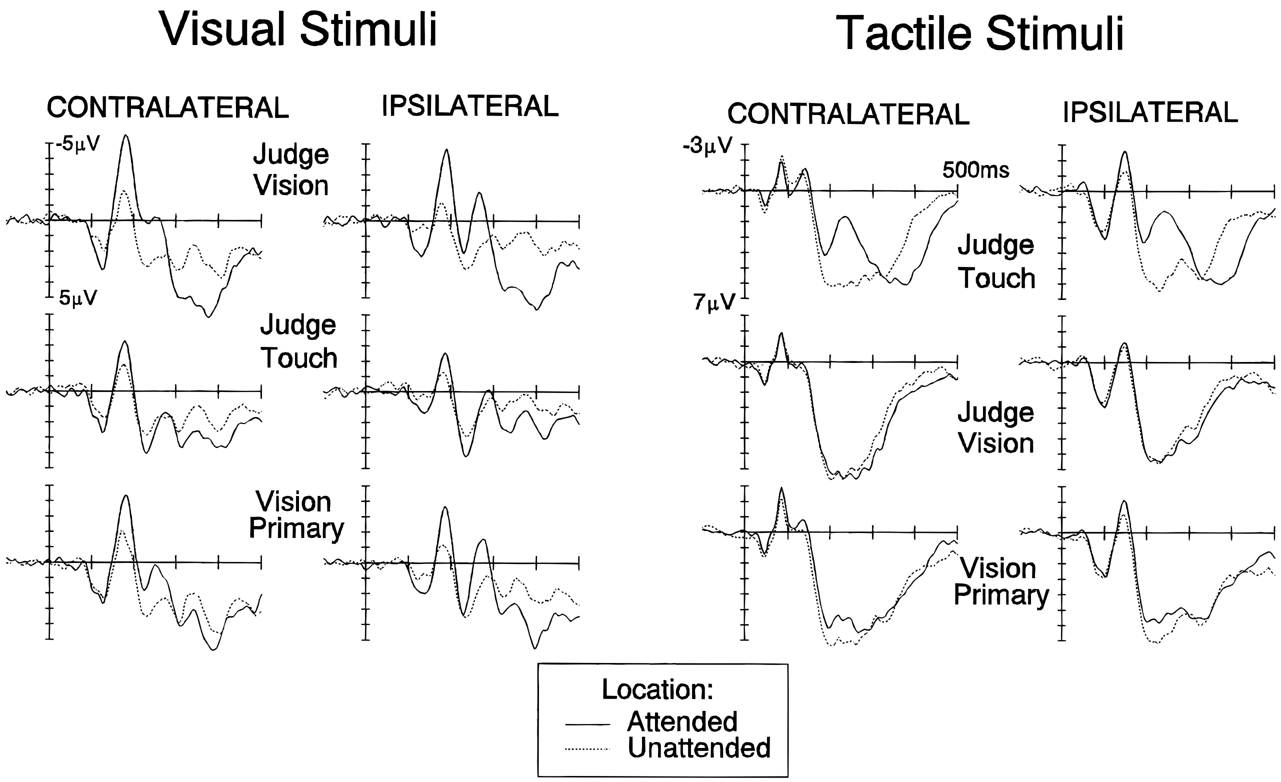

Figure 1. Left: Grand-averaged visual ERPs elicited in the Judge-Vision condition, Judge-Touch condition, and Vision-Primary/Touch-Secondary condition, by visual stimuli at attended locations (solid lines) and unattended locations (dashed lines), at occipital sites contralateral and ipsilateral to the side of stimulus presentation. Right: Grand-averaged somatosensory ERPs elicited in the Judge-Touch condition, Judge-Vision condition, and Vision-Primary/Touch-Secondary condition, by tactile stimuli at attended locations (solid lines) and unattended locations (dashed lines), at central sites contralateral and ipsilateral to the side of stimulus presentation.

unattended difference waveforms. When compared with unattended stimuli, visual stimuli at attended locations elicited an enhanced negativity that started around 140 ms poststimulus. This effect lasted considerably longer in the judge-vision and vision-primary/touch-secondary conditions that in the judge-touch condition and was followed by an enhanced positivity for attended relative to unattended stimuli.[3] In the N1 time range, a main effect of spatial attention, $F(1,11) = 6.54$, $p < .027$, was accompanied by a Spatial attention × Electrode interaction,$F(2,22) = 6.83$, $p < .020$, $\epsilon = 0.565$. No significant attentional effects were obtained at Fz. At Cz and Pz, larger negativities for attended stimuli were present for all three task conditions,all $t(11) > 1.9$, all $p < .04$. In the Nd latency window (210–280 ms poststimulus), main effects of spatial attention were present at midline sites, $F(1,11) = 4.83$, $p < .05$, reflecting enhanced negativities for attended stimuli. Notably, this effect was accompanied by a highly significant Spatial attention × Task interaction, $F(2,22) = 8.44$, $p < .008$, $\epsilon = 0.636$. Significant attentional effects were obtained for all three midline sites in the judge-vision condition, all $t(11) > 2.5$, all $p < .014$, and for Cz and Pz in the vision-primary/touch-secondary condition, both $t(11) > 1.95$, both $p < .039$. In contrast, no attentional ERP modulations were present in the Nd time window for the judge-touch condition (Figure 2).

Effects of Spatial Attention on Somatosensory ERPs

Figure 1 (right half) shows ERPs elicited in the three task conditions by tactile stimuli at central electrodes ipsilateral and contralateral to the stimulated hand. Relative to unattended stimuli, attended stimuli elicited an enhanced negativity that started around 140 ms poststimulus and overlapped with the somatosensory N1 at ipsilateral electrodes. This effect seems largest in the judge-touch condition, smaller in the vision-primary/touch-secondary condition, and absent in the judge-vision condition. A main effect of spatial attention was found in the Nde interval (140–200 ms poststimulus), $F(1,11) = 19.9$, $p < .001$. This effect was present in the judge-touch condition and in the vision-primary/touch-secondary condition, both $F(1,11) > 5.67$, both $p < .036$, but not in the judge-vision condition, $F < 1$ (Figure 1, right). In spite of this difference, no significant Spatial attention × Task interaction was obtained in the Nde time window. Between 200 and 280 ms poststimulus (Ndl latency range), a main effect of spatial attention, $F(1,11) = 20.0$, $p < .001$, again reflecting enhanced negativities elicited by tactile stimuli at attended locations, was accompanied by a highly significant Spatial attention × Task interaction, $F(2,22) = 9.12$, $p < .005$, $\epsilon = 0.675$. In this time range, attentional ERP modulations were elicited in the judge-touch and vision-primary/touch-secondary conditions, both $F(1,11) > 11.5$, both $p < .006$, but they were entirely absent in the judge-vision condition, $F < 1$, (Fig. 1, right). No significant Attention × Stimulus side × Electrode location interactions were found at lateral central electrodes within either analysis window, indicating that effects of spatial attention were of similar size at contralateral and ipsilateral sites.

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[3] This late positivity may in part reflect a P300 elicited in response to events at attended locations because these events require a target/nontarget classification.

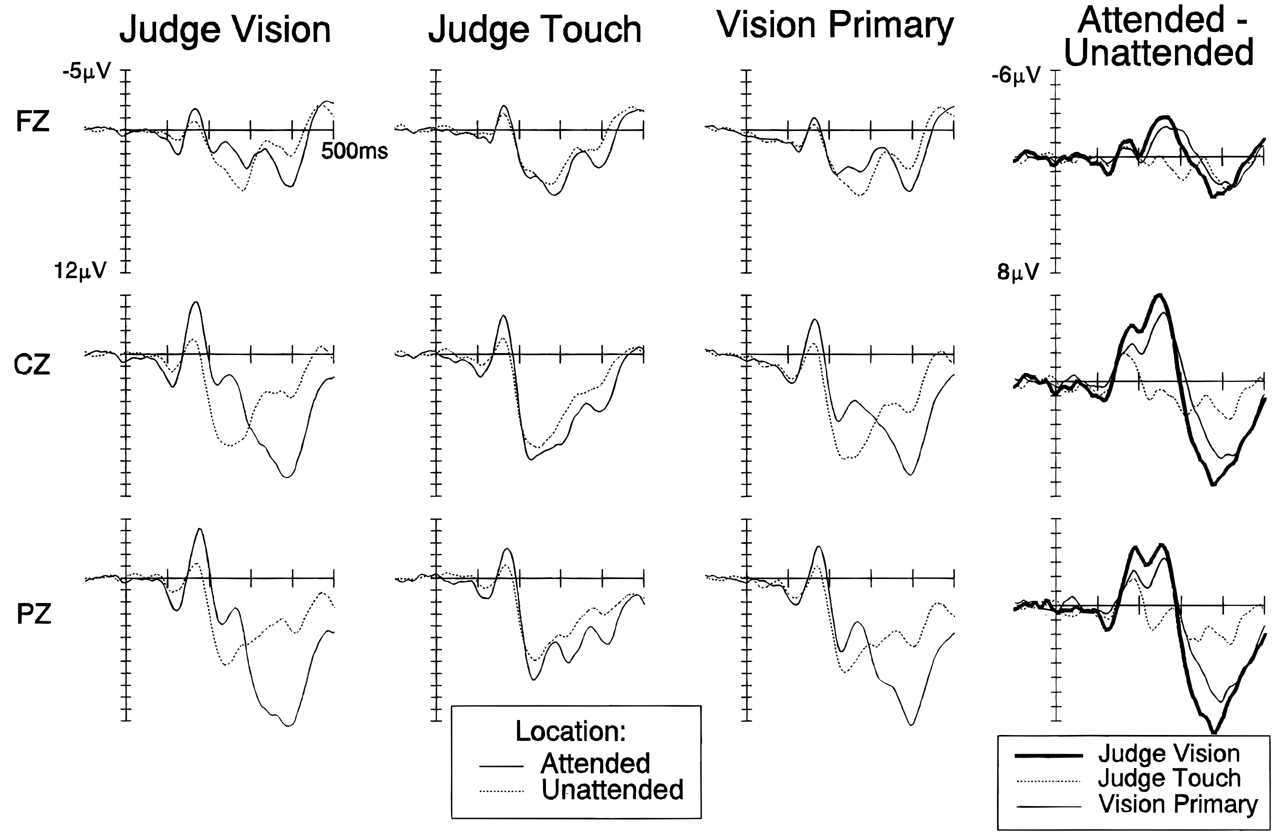

Figure 2. Grand-averaged visual ERPs elicited at midline electrodes in the Judge-Vision condition, Judge-Touch condition, and Vision-Primary/Touch-Secondary condition, by visual stimuli at attended locations (solid lines) and unattended locations (dashed lines). Right: Difference waveforms obtained at midline electrodes by subtracting ERPs to visual stimuli at unattended locations from ERPs to visual stimuli at attended locations in the Judge-Vision condition (thick solid lines), Judge-Touch condition (dashed lines), and Vision-Primary/Touch-Secondary condition (thin solid lines).

Figure 3 shows somatosensory ERPs elicited in the three task conditions at midline electrodes together with the resulting attended minus unattended difference waveforms. When compared with unattended stimuli, tactile stimuli at attended locations elicited an enhanced negativity that started around 130 ms poststimulus. This effect was largest in the judge-touch condition, smaller in the vision-primary/touch-secondary condition, and apparently absent in the judge-vision condition. Main effects of spatial attention were present in the Nde as well as in the Ndl latency windows, $F(1,11) = 8.55$ and 18.81, $p < .014$ and .001, respectively. In the Nde time window, this effect was accompanied by a Spatial attention × Electrode interaction, $F(2,22) = 13.32$, $p < .001$, $\epsilon = 0.820$, and a Spatial attention × Task × Electrode interaction, $F(4,44) = 3.39$, $p < .037$, $\epsilon = 0.641$. Further analyses showed no significant attentional effects at Fz. At Cz and Pz, attentional modulations were present in the judge-touch condition and the vision-primary/touch-secondary condition, all $t(11) > 2.07$, all $p < .032$, but importantly were absent in the judge-vision condition (Figure 3). In the Ndl latency range, a Spatial attention × Electrode interaction, $F(2,22) = 8.97$, $p < .003$, $\epsilon = 0.808$, indicated that attentional negativities were largest at Cz. In addition, a Spatial attention × Task interaction, $F(2,22) = 8.91$, $p < .005$, $\epsilon = 0.700$, and a Spatial attention × Task × Electrode interaction, $F(4,44) = 5.83$, $p < .018$, $\epsilon = 0.378$, were present. Subsequent *t* tests showed that significant Ndl effects were present in the judge-touch condition and in the vision-primary/touch-secondary condition at all three midline sites, all $t(11) > 2.4$, all $p < .018$, but were absent in the judge-vision condition (Figure 3).

The attentional modulations observed for somatosensory ERPs in the Ndl latency range at midline and lateral central electrodes were further investigated by ANOVAs including only data obtained in two of the three task conditions. When the judge-touch condition and the vision-primary/touch-secondary condition were analyzed together, significant Spatial attention × Task interactions were obtained at midline sites, $F(1,11) = 6.4$, $p < .028$, and lateral central electrodes, $F(1,11) = 5.61$, $p < .037$, demonstrating that attentional effects were attenuated in the vision-primary/touch secondary condition relative to the judge-touch condition. When the vision-primary/touch-secondary condition and the judge-vision condition were analyzed together, Spatial attention × Task interactions were again obtained at midline sites, $F(1,11) = 5.19$, $p < .044$, and lateral central electrodes, $F(1,11) = 7.23$, $p < .021$, reflecting the fact that attentional negativities were present in the vision-primary/touch-secondary condition but not in the judge-vision condition.

Discussion

The aim of this ERP study was to investigate cross-modal links in endogenous spatial attention between vision and touch. Recent behavioral evidence (Spence et al., in press) suggests a tendency

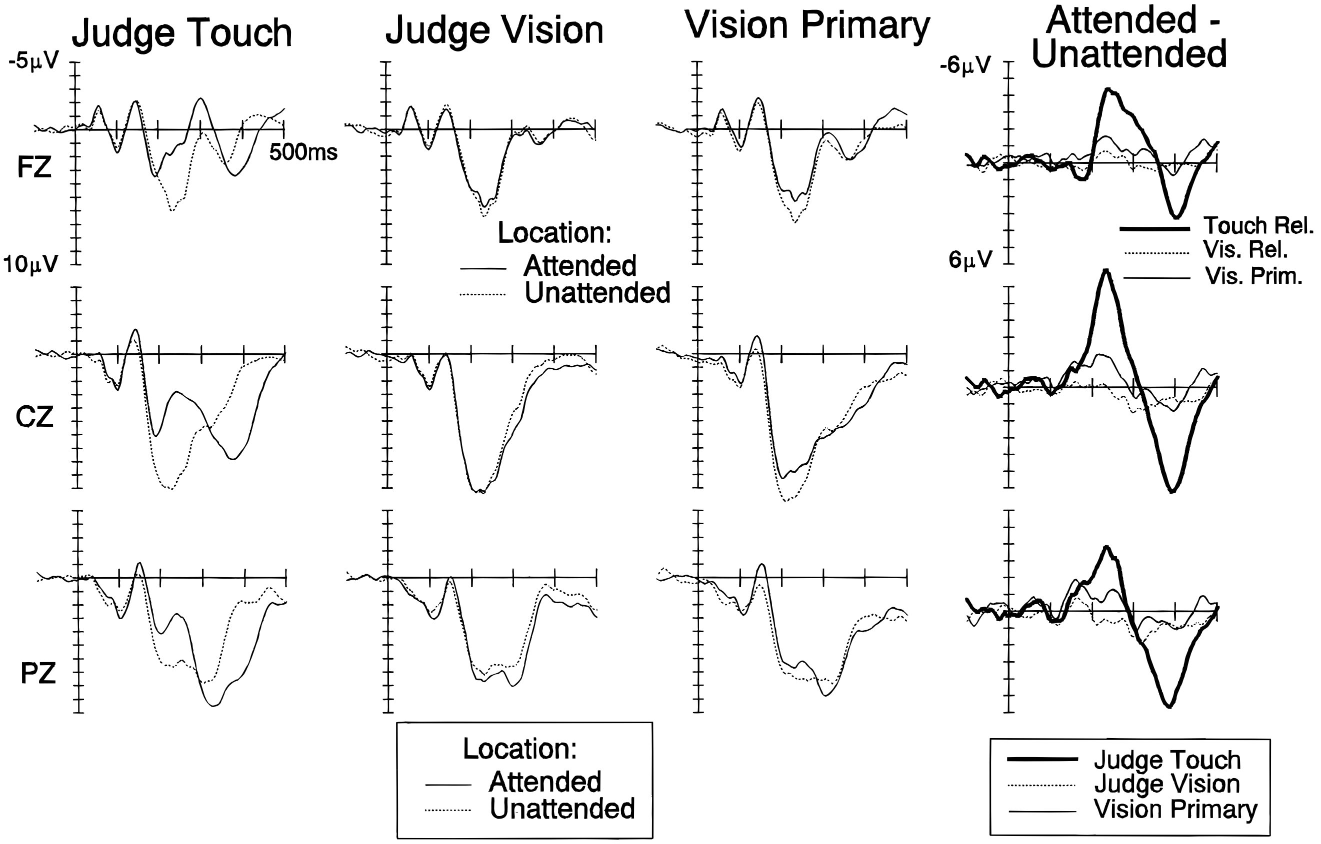

Figure 3. Grand-averaged somatosensory ERPs elicited at midline electrodes in the Judge-Touch condition, Judge-Vision condition, and Vision-Primary/Touch-Secondary condition, by tactile stimuli at attended locations (solid lines) and unattended locations (dashed lines). Right: Difference waveforms obtained at midline electrodes by subtracting ERPs to tactile stimuli at unattended locations from ERPs to tactile stimuli at attended locations in the Judge-Touch condition (thick solid lines), Judge-Vision condition (dashed lines), and Vision-Primary/Touch Secondary condition (thin solid lines).

for spatial attention to shift together in vision and touch. In the present experiment, visual and tactile stimuli were presented equiprobably on the left or right sides, and ERPs to nontarget stimuli were compared for attended versus unattended locations in each modality under conditions when the respective modality was either task relevant or irrelevant.

For visual ERPs, modulations by spatial attention of occipital P1 and N1 components and enhanced negativities for attended stimuli at midline and occipital electrodes were obtained when vision was relevant. Similar modulations by spatial attention were present when touch was task relevant instead, with larger occipital P1 and N1 components and enhanced midline negativities in the N1 time range (160–210 ms poststimulus) for visual stimuli presented at locations that were attended for touch, thus demonstrating cross-modal links. Our finding that spatial attention to the location of tactile stimuli produced systematic modulations of visual ERPs between 100 ms to 200 ms poststimulus provides evidence for the existence of cross-modal links in spatial attention between touch and vision.[4] In the Nd latency window (210–280 ms poststimulus) spatial attention effects were only present when vision was relevant; they were absent when attention was directed to the location of tactile stimuli. Overall, this pattern of results suggests that cross-modal links from touch to vision in endogenous spatial attention primarily affect early stages of visual processing. The cross-modal effects observed for visual ERPs in the present study are similar to the effects reported by Eimer and Schröger (1998) in a study of cross-modal links in spatial attention between audition and vision, where attentional modulations of occipital N1 components plus increased negativities at midline electrodes were similarly found when attention was directed to the location of auditory stimuli.

For somatosensory ERPs, the pattern of results obtained in the present study is more complex. When only touch was task relevant, spatial attention was reflected by enhanced negativities at midline and lateral central electrodes between 140 ms and 280 ms poststimulus, overlapping with the somatosensory N1 component at ipsilateral central electrodes. In contrast to the cross-modal influences seen on visual ERPs, no significant attentional modulations

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[4] These early spatial attention effects on visual ERPs could in part result from undetected deviations from central fixation. In a sustained spatial attention situation, some participants may move their eyes towards the attended location prior to or at the beginning of some experimental blocks and may remain fixated on this position. Such gaze deviations are notoriously difficult to detect on the basis of HEOG recordings. Although participants were strongly instructed to keep fixating on the central cross, several training blocks were presented prior to EEG recording where eye fixation was closely monitored, and if necessary fixation instructions were repeated, this possibility cannot be completely ruled out. Deviations in gaze control cannot, however, account for the effects of spatial attention on somatosensory ERPs.

were found for somatosensory ERPs in the judge-vision condition when touch was entirely response irrelevant. This finding replicates the results obtained in our pilot study. The null influence of visual-spatial attention on somatosensory ERPs in the judge-vision condition appears to be in conflict with the behavioral results of Spence et al. (in press), who found unequivocal psychophysical evidence for symmetric links between vision and touch. However, their psychophysical measures required that events in both modalities always received a response, whereas tactile events were entirely response irrelevant in the judge-vision condition. Consideration of this difference raised the possibility that touch may be decoupled from visual-spatial attention whenever tactile stimuli can be entirely ignored yet may be linked cross-modally whenever tactile stimuli are potentially response relevant, as in Spence et al.'s (psychophysical studies. The present experiment produced supportive evidence for this hypothesis. Although attentional modulations of somatosensory ERPs were absent in the judge-vision condition, clear attentional effects on somatosensory ERPs were elicited in the vision-primary/touch-secondary condition, which was identical in all respects to the judge-vision condition except that participants now also had to respond to rare tactile targets that were equally probable on the left and right. In this condition, tactile stimuli at attended locations elicited enhanced negativities at lateral central and at midline electrodes. Between 140 and 200 ms poststimulus, these effects were comparable in size to the effects obtained in the judge-touch condition. Beyond 200 ms, they were attenuated but still clearly present.

This pattern of results lends support to the idea that although the distribution of spatial attention within vision leaves tactile processing unaffected when tactile stimuli can be entirely ignored, the modalities become linked if touch becomes potentially response relevant. The vocal performance in response to tactile targets in the vision-primary/touch-secondary condition showed an analogous influence of visual-spatial attention, replicating the link between visual attention and touch that was demonstrated behaviorally by Spence et al. (in press) when touch was response relevant. These findings emphasize the value of ERPs for the study of attentional mechanisms. In contrast to behavioral measures, ERPs can be recorded under conditions of fully focused attention when unattended stimuli are entirely response irrelevant. In the present study, cross-modal links from vision to touch could only be observed when touch was potentially relevant but not when attention was fully focused within vision. This insight could not have been obtained exclusively on the basis of behavioral measures and thus adds to the psychophysical results of Spence et al. and qualifies their conclusions.

The results obtained for somatosensory ERPs suggest that touch is functionally different from both vision and audition with respect to cross-modal links in spatial attention. Modulations of visual and auditory ERPs by spatial attention directed in the other modality are found even when the modality in question is entirely task irrelevant (Eimer & Schröger, 1998), indicating that visual and auditory processing cannot be completely decoupled from spatial attention. Similarly, visual ERPs showed modulation by spatial attention to tactile stimuli in the judge-touch condition, indicating that vision cannot be decoupled from spatial orienting within another modality. In contrast, visual-spatial attention leaves somatosensory ERPs unaffected when touch is task irrelevant. We can only speculate about the functional significance of this difference. The presence of asymmetrical links in spatial attention between vision and touch could reflect differences in the precision of spatial coding between these modalities. Because of the superior spatial precision within vision, tactile coordinates may be remapped onto visual space when attention is directed within touch but not vice versa. If this were the case, one should predict similar asymmetries between vision and audition, a prediction not supported by current data (Eimer & Schröger, 1998; Spence & Driver, 1996). Alternatively, one may argue that audition and vision cannot be decoupled from cross-modal links because these two modalities both process distal information across considerable distances and from similar sources. By contrast, touch is a more proximal sense (Gibson, 1966) that only codes information from objects in direct contact with the body surface. In many situations in daily life (e.g., when students sit in a lecture theatre), ongoing tactile information from the body as it rests in place is irrelevant to the more distant events to which the person attends (e.g., the sight and sounds of the lecturer) and should be filtered out. One way to achieve this filtering may be to prevent spatially selective modulations of somatosensory processing by decoupling any links that exist with spatial attention in other modalities, except when somatosensory information becomes potentially task relevant.

Overall, the present experiment provides the first ERP evidence for cross-modal links in endogenous spatial attention from touch to vision and (provided that tactile stimuli are potentially response relevant) from vision to touch. These findings fit with the recent psychophysical results of Spence et al (in press). They may also relate to the multimodal neurons recently observed in the primate brain by single-unit recording in monkeys. Neurons in posterior parietal cortex and ventral premotor cortex have been found that respond to both tactile and visual stimulation from similar locations in external space (Graziano & Gross, 1996). It seems plausible that such neurons may be involved in establishing the cross-modal links in spatial attention between vision and touch that are reflected by attentional modulations of visual and somatosensory ERPs, as observed in the present study. The fact that such cross-modal modulations can be seen in relatively early sensory ERP components raises the possibility that backprojections, from multimodal neurons to unimodal neurons earlier in the processing stream may also play a role in the cross-modal links we have documented.

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RECEIVED June 31, 1999; ACCEPTED October 27, 1999