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RESEARCH ARTICLE

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Crossmodal and intermodal attention modulate event-related brain potentials to tactile and auditory stimuli

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Abstract An increasing number of animal and human studies suggests that different sensory systems share spatial representations in the brain. The aim of the present study was to test whether attending to auditory stimuli presented at a particular spatial location influences the processing of tactile stimuli at that position and vice versa (crossmodal attention). Moreover, it was investigated which processing stages are influenced by orienting attention to a certain stimulus modality (intermodal attention). Event-related brain potentials (ERPs) were recorded from 15 participants while tactile and auditory stimuli were presented at the left or right side of the body midline. The task of the participants was to attend to either the auditory or to the tactile modality, and to respond to infrequent double-stimuli of either the left or right side. Results showed that spatial attention modulated both early and late somatosensory and auditory ERPs when touch and tones were relevant, respectively. Moreover, early somatosensory (N70–100, N125–175) and auditory (N100–170) potentials, but not later deflections, were affected by spatial attention to the other modality, suggesting bi-directional crossmodal links between hearing and touch. Additionally, ERPs were modulated by intermodal selection mechanisms: stimuli elicited enhanced negative early and late ERPs when they belonged to the attended modality compared to those that belonged to the unattended modality. The present results provide evidence for the parallel influence of spatial and intermodal selection mechanisms at early processing stages while later processing steps are restricted to the relevant modality.

Keywords Spatial attention · Tactile · Auditory · Multisensory · Crossmodal

Introduction

Selective attention is the mechanism that allows us to focus on important input while ignoring unimportant events. The neurophysiological mechanisms of selective attention for auditory, visual, or tactile stimuli have been studied extensively with event-related brain potentials (ERPs). In these studies ERPs to attended stimuli were compared with those to the same stimuli but when they were unattended. Characteristic attention-related modulations of ERPs were observed although they were elicited by physically identical stimuli (Hillyard et al. 1973; for a review see Woods 1990).

In everyday life we are not only exposed to stimuli of a single modality, but rather, most of the time, events are multimodal, i.e. they provide adequate input to more than one sensory system. For example, when listening to a speaker, we do not only hear his or her voice but also see the lip movements. The additional visual cues significantly improve comprehension, especially in noisy conditions (Sumby and Pollack 1954). An example of auditory-tactile interaction is the so called parchment-skin illusion. In this experiment participants rubbed their palms together while the sound elicited by the rubbing was played back to them via headphones. When the frequency or sound level of the auditory feedback was changed, the perception of the skin surface was significantly modified (Jousmäki and Hari 1998).

Exogenous spatial cueing paradigms have demonstrated that uninformative cues modify the processing of the following target both when cue and target were of the same and different modalities (Spence and Driver 1997; Spence et al. 1998, 2000a). Moreover, when participants expected targets of one modality at one spatial position (endogenous attention) the processing of rare stimuli of a second modality was faster when presented at the attended position, although they were more likely to

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appear at a different spatial position (Spence and Driver 1996; Spence et al. 2000b). These results suggest that there are crossmodal links in both exogenous and endogenous covert spatial attention.

ERP studies provide additional information about the processing stage at which input from different modalities is integrated. In studies assessing *intermodal attention effects*, the amplitude of early ERP components was found to be enhanced for visual and auditory stimuli when the modality was attended compared to when another modality was attended (Alho et al. 1992, 1994; de Ruiter et al. 1998; Talsma and Kok 2001; Woods et al. 1992).

Other studies of multimodal attention have focused on the question of how different modalities are integrated. The spatial position of stimuli is one important feature for binding input from different modalities. In these studies random streams of stimuli of two modalities were delivered while participants had to attend to one modality at one spatial position and to ignore stimuli at other positions and all stimuli of the other modality. It has been assumed that, if there are *crossmodal links* between different modalities, a spatial attention effect should not only be seen for stimuli of the attended modality but also of the unattended one. Such crossmodal links seem to exist between hearing and vision (Eimer and Schröger 1998; Hillyard et al. 1984; Teder-Sälejärvi et al. 1999) and between vision and touch (Eimer and Driver 2000; Eimer et al. 2001, 2002). For sustained spatial attention, Eimer and Driver (2000) found spatial attention effects for visual ERPs when touch was attended but not vice versa. Somatosensory ERPs were modulated by visual spatial attention only when tactile stimuli were made task-relevant. This result suggests that it might be possible to decouple the tactile modality from vision. Moreover, in an exogenous cueing task with tactile cues and visual targets, Kennett et al. (2001) showed that exogenously elicited orienting to tactile stimuli affected ERPs to visual stimuli.

Little is known about the link between hearing and touch. Eimer et al. (2001, 2002) showed that attending tactile stimuli modulated ERPs to auditory stimuli but not vice versa. In these experiments the position to be attended was indicated by a symbolic cue at the beginning of each trial (transient attention). Therefore, it remains unknown whether attending auditory stimuli modulates ERPs to tactile stimuli under sustained rather than transient attention conditions.

The present study, therefore, used a sustained attention paradigm (Hillyard et al. 1984) to evaluate the effects of spatial and intermodal attention on the processing of tactile and auditory stimuli. Stimuli of both modalities were presented randomly from the left and right side. Participants had to attend to one modality on one side and to respond to infrequent deviant stimuli of that modality and that side only. By the systematic variation of the attended modality and location, ERPs to physically identical stimuli can be compared when they belong to the attended modality and location (M+/L+), to the attended modality but unattended location (M+/L–), to the unattended modality but attended location (M–/L+), and to the unattended modality and unattended location (M–/L–). This allows to test unimodal and crossmodal spatial attention effects as well as intermodal attention effects. A *unimodal spatial attention* effect is seen by comparing ERPs to M+/L+ stimuli with those elicited by M+/L– stimuli. If ERPs evoked by M–/L+ stimuli differ from those evoked by M–/L– stimuli it is justified to conclude that a *crossmodal attention effect* exists. *Intermodal attention effects* are revealed by comparing ERPs to M+/L+ stimuli with those to M–/L+ stimuli and ERPs to M+/L– stimuli with those to M–/L– stimuli.

Based on previous studies (see above), we expected early ERPs (starting around 100 ms) to be more pronounced to stimuli when presented from the attended side than unattended side. For somatosensory ERPs these effects were expected to be maximal at centro-parietal electrodes contralateral to the stimulated finger, while the auditory attention effects were expected to have a fronto-central scalp topography (Woods 1990).

The study aimed to find out whether spatial attention influences both the processing of stimuli of the attended modality (*unimodal spatial attention effect*) and that of stimuli of the unattended modality (*crossmodal spatial attention effect*). Moreover, we asked whether the selection operations are mediated by the same brain systems. For this purpose we compared the scalp distribution of unimodal and crossmodal spatial attention effects.

Furthermore, we hypothesized that stimuli belonging to the attended modality elicit more pronounced ERPs than when they belong to the unattended modality (*intermodal attention effect*; e.g. Alho et al. 1994).

Methods

Participants

Sixteen students of the Philipps-University Marburg participated in the experiment. They received course credits or were paid for participation. One participant had to be excluded because of technical problems. Of the remaining 15 participants (8 women, mean age 24 years, range 20–32 years), 12 were right-handed and 3 were left-handed. They all reported normal or corrected-to-normal vision, normal hearing, and tactile sensitivity. Participants gave written informed consent. The experiment was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and with the ethics requirements of the University of Marburg.

Materials

The auditory stimuli were bursts of white noise (68 dBA) presented from two loudspeakers. To avoid participants using possible differences in the frequency characteristics of the left and right speaker to localize the sounds, slightly different sounds (low-pass filtered with an upper cutoff at 16 and 14 kHz, respectively) were delivered with equal probability from the left and right side. The loudspeakers were located 37° to the left and right side at a distance of 43 cm from a chin rest. Auditory standard stimuli (P=0.80) had a duration of 200 ms. Deviants (P=0.20) were two bursts of 90 ms separated by a 20 ms silent interval (double tones).

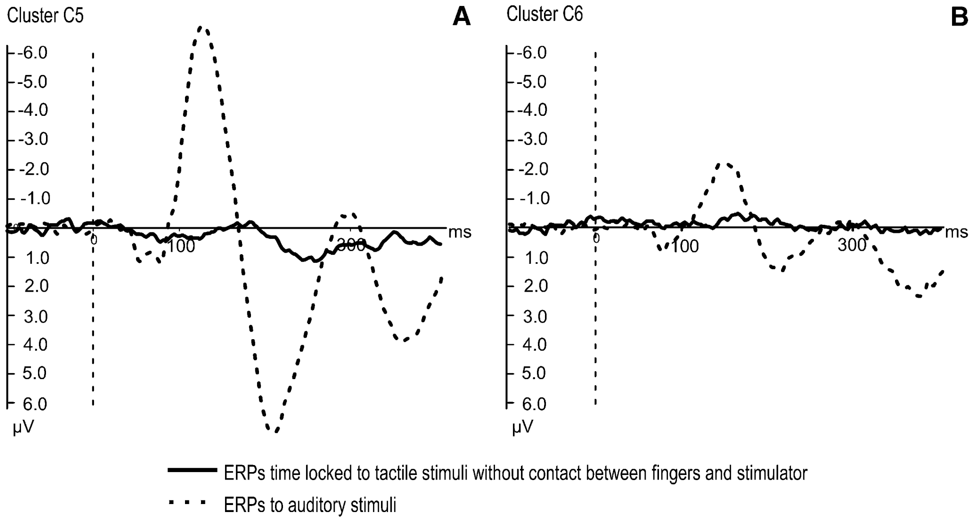

Fig. 1A,B Results of the control experiment with two additional participants to ensure that the faint noise of the tactile stimulators did not evoke auditory event-related potentials (ERPs). Grand average ERPs time-locked to the "tactile" stimuli (but there was no contact between participants' fingers and the tactile stimulators). For comparison, ERPs to the auditory stimuli are shown as well. **A** ERPs at a central electrode cluster (C5) where auditory ERPs were maximal. **B** ERPs at a temporal electrode cluster (C6) where tactile ERPs were maximal

The tactile stimuli were delivered by metallic pins (1.4 mm in diameter) situated underneath the distal part of the participant's index fingers. Stimuli were presented by moving the pins up for 0.7 mm orthogonal to the skin surface. The tactile stimulators were arranged directly in front of the loudspeakers so that auditory and tactile stimuli were delivered from positions in close spatial proximity. For tactile standard stimuli (P=0.80) the pins were moved up for 200 ms. For deviants (P=0.20) this contact was interrupted for 10 ms (double tactile stimuli). Pilot studies had shown that the discrimination between standards and deviants was of equal difficulty with 20 and 10 ms gaps for auditory and tactile stimuli, respectively. The faint noise of the tactile stimuli (38 dBA) was masked by white noise presented over headphones (55 dBA). Participants reported that they were not able to hear when the pins moved up and down. This was confirmed in two additional participants who received the same stimuli as the others but whose fingers did not touch the tactile stimulators. They performed the auditory attention task. ERPs were averaged time-locked to the tactile stimuli. As seen in Fig. 1 no "auditory" ERP was elicited by the noise of the tactile stimuli. Therefore, we concluded that the tactile stimuli were neither consciously heard by the participants nor did they evoke auditory ERPs.

Procedure

The experiment took place in an electrically shielded and sound-attenuating room. Participants sat at a table with their arms lying on its top, the index fingers were resting on the tactile stimulators. An adjustable chin rest was used to immobilize the participant's head.

Auditory and tactile stimuli were delivered with equal probability and in a random sequence from the left and right side. The interstimulus interval was varied randomly between 650 and 950 ms (mean 800 ms).

The experiment consisted of 12 blocks of 200 stimuli each. For one half of the blocks the participants were instructed to attend to tactile stimuli on the left or right side ("attend touch left" and "attend touch right") and on the other half to attend to auditory stimuli on the left or right side ("attend tones left" and "attend tones right"). They had to detect rare deviant stimuli (i.e. double stimuli) of the attended modality at the attended side. Deviant detection had to be signaled by a foot pedal response, on half of each of the four conditions with the left and on the other half with the right foot. Participants were asked to respond as fast and as accurately as possible. The maximal allowed response time was 2000 ms measured from the onset of the target stimuli.

In the first half of the experiment participants had to attend to one modality and in the second half to the other. The location to be attended was changed every block. The particular modality and location that was attended first was balanced across participants. Two additional practice blocks were run, one for "attend touch" and one for "attend tones".

Electroencephalograph (EEG) recording

The EEG was recorded from 61 scalp electrodes (non-polarizable Ag/AgCl electrodes) that were mounted at equal distance in an elastic cap (Easy Cap; FMS, Herrsching-Breitbrunn, Germany). Recordings were referred to the right ear lobe. Offline, an averaged right/left ear lobe reference was calculated using an additional left ear lobe recording.

Vertical eye movements were monitored (electrooculogram, EOG) with an electrode below the right eye against the reference. Horizontal eye movements were recorded with two electrodes placed at the outer canthi of each eye (bipolar recording).

Electrode impedance was kept below 5 kΩ for scalp electrodes and below 10 kΩ for eye electrodes. This was achieved by preparing the skin with an abrasive gel (Every, Gelimed, Negernbötel, Germany) and isopropanol. Conductivity between the skin and the electrodes was attained by an electrolyte paste (Eci Electrogel; Electrocap International, Eaton, OH, USA). Recordings were amplified (Synamps amplifiers; Neuroscan, Sipplingen, Germany) with a band-pass of 0.1–100 Hz. The EEG and EOG were recorded continuously and digitized at 500 Hz.

Participants were asked to avoid any head and eye movements during blocks. To suppress eye movements they wore swimming goggles equipped with little soft cushions.

Data analyses

Misses, false alarms, and mean reaction times were calculated separately for each modality and side of stimulation. As the gap interval for tactile and auditory stimuli was not the same, the earliest time-point at which standards and targets differed was 95 ms

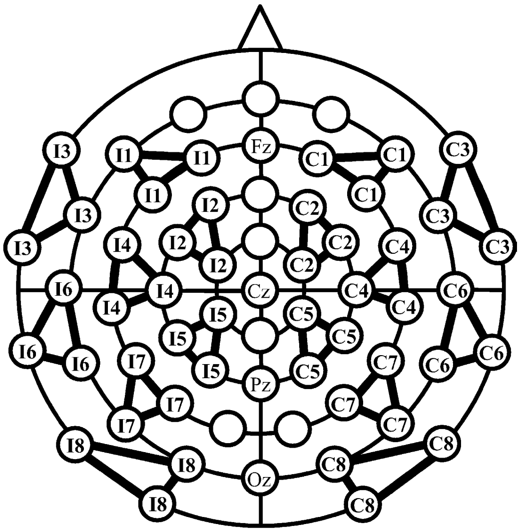

Fig. 2 Schematic drawing of the electrode montage. Three adjacent electrodes were assigned to one cluster. Clusters were named relative to side of stimulation as ipsilateral (*I*) and contralateral (*C*) and numbered from 1 to 8 according to their location along the anterior-posterior dimension

after stimulus onset for tactile targets and 90 ms for auditory targets. Therefore, reaction times were calculated from gap onset. Analyses of variance (ANOVAs) were conducted with the repeated measurement factors Stimulus modality (auditory vs tactile) and Side of stimulation (left vs right).

Somatosensory and auditory ERPs to standard stimuli were averaged separately for each participant and condition (attend touch left, attend touch right, attend tones left, attend tones right). All measures were taken relative to a 100-ms pre-stimulus baseline. ERPs to attended and unattended stimuli were separately pooled over the left and right side. For this purpose electrodes had to be remapped to ipsilateral and contralateral recording sites with respect to the side of stimulation.

In three participants, one to three channels with recording artifacts were replaced by a linear interpolation of adjacent electrodes. Segments with response errors, eye movement artifacts (difference of more than 100 μV between two values in a segment of the horizontal or vertical EOG channels), amplifier saturation or other artifacts (channels with voltage differences of more than 150 μV between two sample points) were discarded. Three adjacent electrodes were clustered as shown in Fig. 2. In the following, we refer to clusters 1 and 3 as frontal clusters, to clusters 2, 4 and 5 as central clusters, to cluster 6 as temporal cluster, to cluster 7 as parietal cluster, and to cluster 8 as occipital cluster.

For the statistical analyses mean amplitudes were calculated for selected time windows: for somatosensory ERPs 70–100 ms (N70–100), 125–175 ms (N125–175) and 200–280 ms (N200–280), and for auditory ERPs 100–170 ms (N100–170) and 200–350 ms (N200–350). Mean amplitudes were analyzed separately for somatosensory and auditory ERPs with an ANOVA comprising four repeated measurement factors: Spatial attention (attended vs unattended side), Intermodal attention (attend touch vs attend tones), Hemisphere (contralateral vs ipsilateral to side of stimulation) and Cluster (electrode cluster 1–8). As we expected the attention effects to be more pronounced over the contralateral hemisphere, particularly for the tactile stimuli, separate ANOVAs for the contralateral and ipsilateral hemisphere were also run.

To test whether unimodal (M+/L+ minus M+/L–) and crossmodal (M–/L+ minus M–/L–) spatial attention effects have a similar or different scalp distribution, difference amplitudes (“attended side” minus “unattended side”) were computed, inverted in polarity and normalized over electrodes separately for each subject and intermodal attention condition (mean 5, SD 2). By using a normalization procedure, amplitude and variance differences among conditions (and participants) are eliminated and only topographical information is retained in the data (McCarthy and Wood 1985). The normalized values reflect the standardized differences from the average amplitude computed over electrodes; larger values represent a larger relative negativity. Normalized difference scores were submitted to a repeated measurement ANOVA with the factors Intermodal attention (attend touch vs attend tones), Hemisphere (contralateral- vs ipsilateral to stimulation) and Cluster (1–8).

All statistics were computed with the software package SPSS using subroutine GLM for repeated measurements. Huynh-Feldt-corrected *P*-values are reported in the Results section.

Results

Behavioral Data

Participants missed 8.94% (SE 1.67) of the tactile target stimuli and 6.72% (SE 1.04) of the auditory target stimuli. They committed 0.34% (SE 0.10) and 0.16% (SE 0.03) false alarms for tactile and auditory stimuli, respectively. Stimulus modality (auditory vs tactile) or Side of stimulation (left vs right) had no effect on misses or false alarms (all $P>0.10$).

The mean reaction time measured from gap onset was 506.53 ms (SE 13.88) for tactile and 522.41 ms (SE 14.08) for auditory target stimuli. Neither Stimulus modality nor Side of stimulation significantly affected reaction times (all $P>0.10$).

EEG Data

Somatosensory ERPs

As seen in Fig. 3, ERPs to somatosensory stimuli started to differ as a function of attention around 70 ms after stimulus onset: ERPs were more negative to stimuli of the attended side than of the unattended side[1] (see Fig. 3B) and to stimuli of the attended modality than unattended modality (see Fig. 3C).

Time epoch 70–100 ms. In this early time window somatosensory ERPs to stimuli of the attended side were more negative than ERPs to stimuli of the unattended side. This was true for both the attend touch condition (*thick lines* in Fig. 3A) and for the attend tones condition (*thin lines* in Fig. 3A). Moreover, somatosensory ERPs were more negative in the attend touch condition than in the attend tones condition. These effects were not independent of each other and were not equally pronounced at all electrode sites [Spatial attention × Intermodal attention × Hemisphere × Cluster: $F_{(7,98)}=2.66$, $P=0.040$].

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[1] When we speak about attended versus unattended side we mean ERPs elicited by the same stimuli when their spatial position was attended or unattended, respectively.

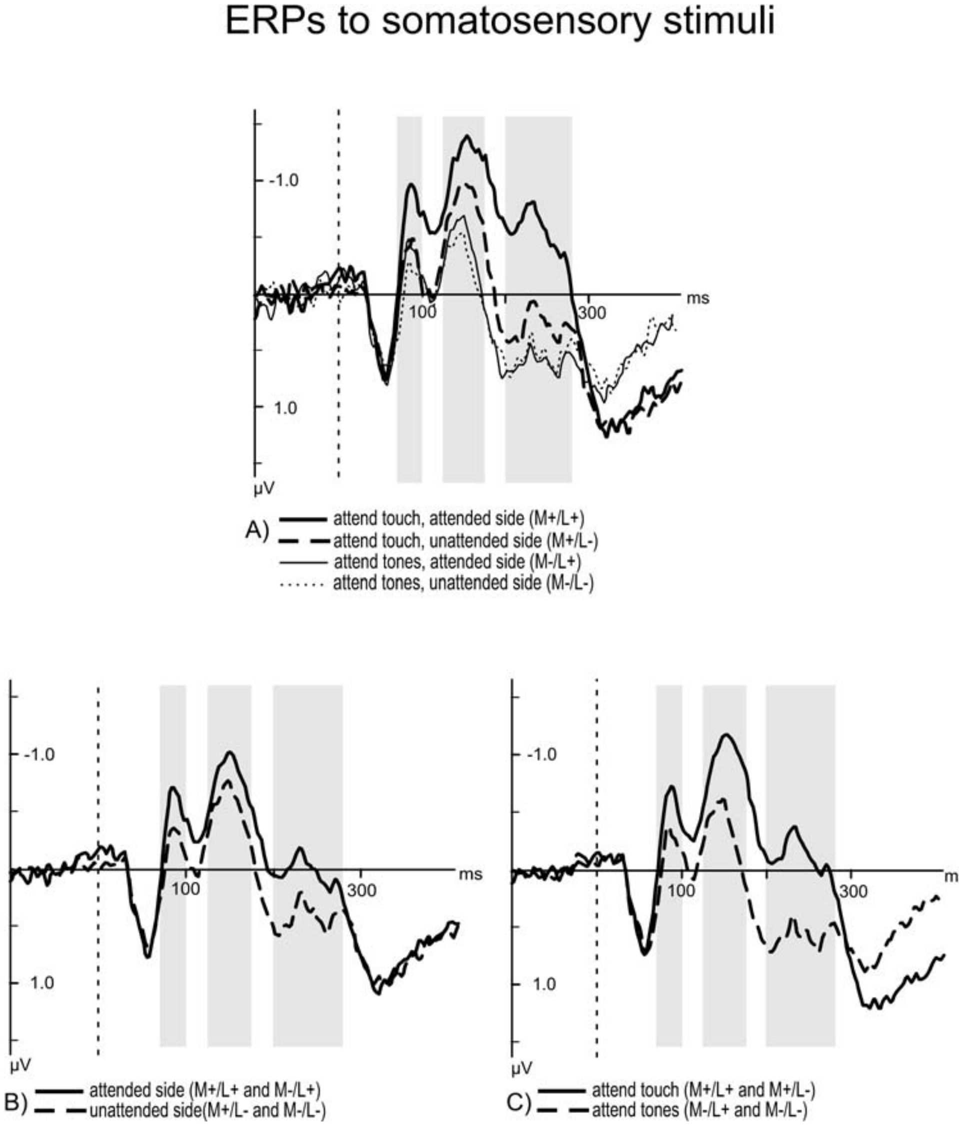

Fig. 3A–C Grand average event-related potentials (ERPs) to somatosensory standard stimuli at a contralateral temporal electrode cluster (C6). **A** ERPs for all four attention conditions are superimposed. **B** ERPs to stimuli presented at the attended side (*solid line*) versus unattended side (*dashed line*) collapsed across intermodal attention conditions. **C** ERPs to stimuli when touch was attended (*solid line*) versus when tones were attended (*dashed line*) collapsed across spatial attention conditions. Time windows used in the statistical analyses are marked *gray*. Negativity is up

Spatial attention modulated the N70–100 at contralateral electrodes only [contralateral: main effect of Spatial attention $F_{(1,14)}=5.12$, $P=0.040$; ipsilateral: no effects of Spatial attention, all $P>0.30$]. The effect was most prominent at frontal, central and temporal clusters (main effect of Spatial attention for clusters C1 and C6, all $P<0.02$; Spatial attention × Intermodal attention for cluster C4, $P=0.031$; see Fig. 4). At central cluster C4, the spatial attention effect was larger when the tactile modality was attended as compared to the attend tones condition. Post hoc tests separately for the intermodal attention conditions showed a significantly enhanced negativity for stimuli of the attended side for the attend touch condition ($P=0.002$, one-tailed t-test) and a trend towards an enhanced negativity for the attend tones condition ($P=0.085$). Although there was no significant interaction between Spatial attention and Intermodal attention at other clusters, separate post hoc comparisons for the attend touch and attend tones conditions of these clusters were run as well. When touch was attended (unimodal spatial attention effect), ERPs to stimuli of the attended side were more negative than ERPs to stimuli of the unattended side at most contralateral clusters (all $P<0.05$, except C7 and C8). When tones were attended (crossmodal spatial attention effect), post hoc comparisons showed an enhanced negativity for stimuli of the attended side at contralateral clusters C1 ($P=0.031$) and C6 ($P=0.059$).

Intermodal attention affected the N70–100 at contralateral and ipsilateral clusters [Intermodal attention × Cluster contralateral $F_{(7,98)}=3.01$, $P=0.028$; ipsilateral $F_{(7,98)}=5.90$, $P=0.002$]. Over the contralateral hemisphere the N70–100 was more negative when the tactile modality was attended than when the auditory modality was attended (main effect of Intermodal attention at clusters C3 and C6, all $P<0.02$). This effect had a positive polarity over the ipsilateral hemisphere; here, ERPs to tactile stimuli were more positive when touch was attended than in to the attend tones condition (main effect of Intermodal attention at clusters I1, I2, and I3, all $P<0.04$).

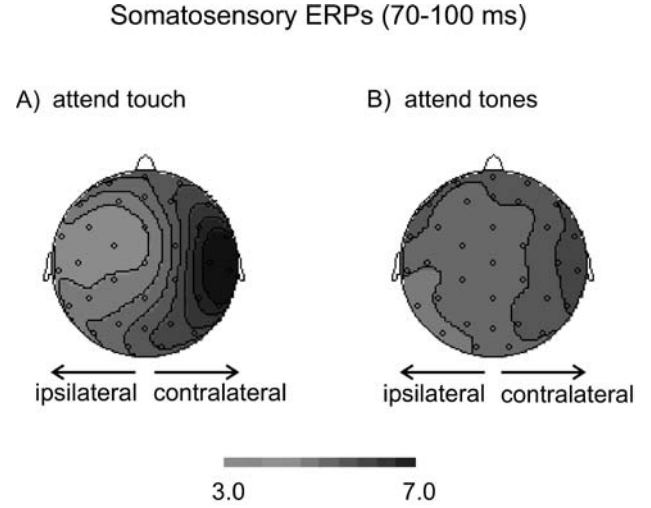

Fig. 4A,B Top view of the normalized topography (mean 5, SD 2) of the spatial attention effect for somatosensory event-related potentials (ERPs) between 70 and 100 ms. **A** Attend touch condition (M+/L+ minus M+/L–). **B** Attend tones condition (M–/L+ minus M–/L–). Larger values (*darker shading*) indicate a relatively more negative amplitude

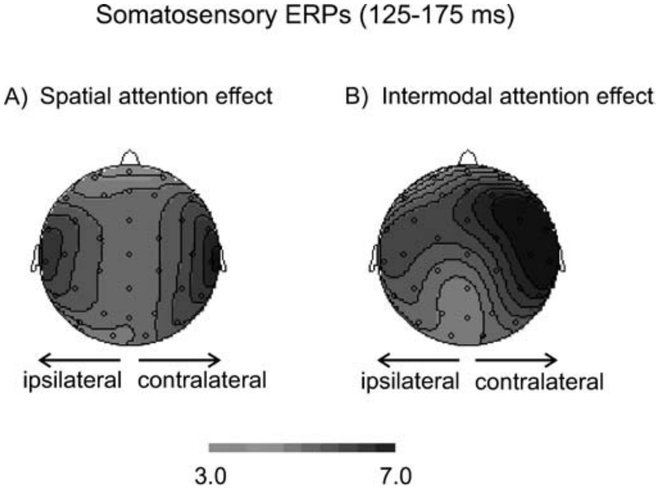

Fig. 5A,B Top view of the normalized topography (mean 5, SD 2) for somatosensory event-related potentials (ERPs) between 125 and 175 ms. **A** Spatial attention effect [(M+/L+ and M–/L+) minus (M+/L– and M–/L–)]. **B** Intermodal attention effect [(M+/L+ and M+/L–) minus (M–/L+ and M–/L–)]. Larger values (*darker shading*) indicate a relatively more negative amplitude

Time epoch 125–175 ms. The N125–175 to stimuli of the attended side was more negative than that of the unattended side. This was seen for the attend touch condition and the attend tones condition (marginally significant main effect of Spatial attention [$F_{(1,14)}$=4.41, P=0.054].

A significant Spatial attention effect was seen for the contralateral hemisphere [main effect of Spatial attention $F_{(1,14)}$=5.98, P=0.028], which was reliable for central and temporal clusters (for C4 and C6 P<0.02; see Fig. 5A).

The lack of a significant Spatial attention × Intermodal attention interaction suggests that the N125–175 was more negative for stimuli of the attended than the unattended side' irrespective of tactile stimuli being attended or not. Nevertheless, we ran separate ANOVAs for the unimodal and crossmodal spatial attention effects. A marginal significant main effect of Spatial attention was revealed for the contralateral hemisphere [$F_{(1,14)}$=3.94, P=0.067] in the attend touch condition. The unimodal effect was most pronounced at centro-temporal clusters of both hemispheres (for C4, C6, I4, and I6, all P<0.05). For the attend tones condition, a significant Spatial attention × Hemisphere × Cluster interaction [$F_{(7,98)}$=3.35, P=0.044] was obtained. Cross-modal spatial attention effects were found for frontal and central clusters which were significant for clusters I3 and I4 (P<0.05) and marginal significant at cluster I1 (P=0.052).

The N125–175 was more negative when the tactile modality was attended than when the auditory modality was attended. The Intermodal attention effect was larger over the contralateral hemisphere than over the ipsilateral [Intermodal attention × Hemisphere $F_{(1,14)}$=12.68, P=0.003]. Nevertheless, the Intermodal attention effect reached significance level for both hemispheres [contralateral: Intermodal attention × Cluster $F_{(7,98)}$=4.58, P=0.020; ipsilateral: Intermodal attention × Cluster $F_{(7,98)}$=4.10, P=0.025]. The Intermodal attention effect was significant for most clusters (all P<0.05, except C8, I1, and I8) with a maximum over contralateral central and frontal clusters (see Fig. 5B).

Time epoch 200–280 ms. In time window 200–280 ms, a spatial attention effect was only seen when the somatosensory modality was attended [Spatial attention × Intermodal attention × Cluster $F_{(7,98)}$=5.58, P=0.010]. The Spatial attention × Intermodal attention interaction was significant for most clusters of the contralateral and ipsilateral hemispheres (all P<0.01, except clusters C1, C3, I1, and I3). The maximum of the Spatial attention effect when touch was attended was seen at contralateral central clusters (C2 and C4), although significantly more negative potentials were recorded for spatially attended versus unattended stimuli over both hemispheres (all P<0.02, except clusters C1, C3, I1, and I3).

The N200–280 was more negative when touch was relevant than when tones were attended. This effect was significant at most clusters (all P<0.03, except clusters I1 and I3) and had its maximum over the contralateral hemisphere at central and temporal clusters [C4 and C6; Intermodal attention × Hemisphere × Cluster $F_{(7,98)}$=4.05, P=0.018]. Moreover, the Intermodal attention effect was more pronounced for stimuli from the attended than from the unattended side (see above: Spatial attention × Intermodal attention × Cluster). For the attended side the Intermodal attention effect reached significance at almost all clusters (all P<0.03, except clusters C1, I1, and I3), while for the unattended side it was reliable only at

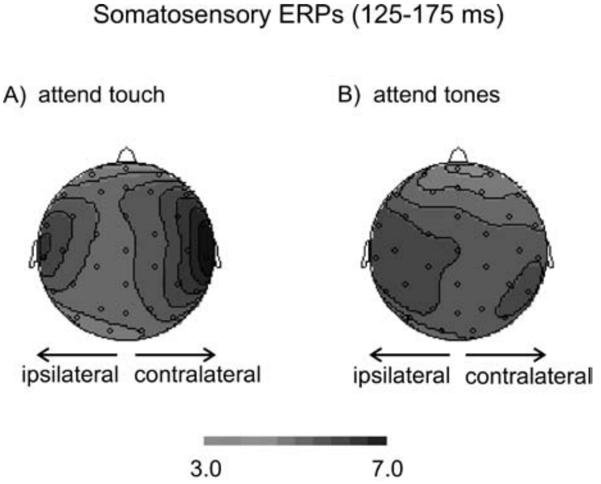

Fig. 6A,B Top view of the normalized topography (mean 5, SD 2) of the spatial attention effect for somatosensory event-related potentials (ERPs) between 125 and 175 ms. **A** Attend touch condition (M+/L+ minus M+/L–). **B** Attend tones condition (M–/L+ minus M–/L–). Larger values (*darker shading*) indicate a relatively more negative amplitude

contralateral clusters (for clusters C3, C4, C6, and C8 $P<0.04$).

Topography. An ANOVA with normalized difference amplitudes (attended side minus unattended side) as dependent variable for time epoch 70–100 ms revealed a significant Intermodal attention × Hemisphere × Cluster interaction [$F_{(7,98)}=2.92$, $P=0.033$, see Fig. 4]. However, separate ANOVAs for each hemisphere did not confirm any significant interaction with Intermodal attention. For time window 125–175 ms, no significant interaction with Intermodal attention was obtained, suggesting that there were no topographical differences between unimodal and crossmodal spatial attention effects (see Fig. 6).

As the results suggest a separate selection mechanism for spatial position and modality, we ran post hoc comparisons between the topography of the spatial attention effect and the intermodal attention effect. For this purpose difference amplitudes of attended side minus unattended side collapsed across intermodal attention conditions [spatial attention effect: (M+/L+ and M–/L+) minus (M+/L– and M–/L–)] and attended modality minus unattended modality collapsed across spatial attention conditions [intermodal attention effect: (M+/L+ and M+/L–) minus (M–/L+ and M–/L–)] were normalized separately for each participant (see Fig. 3B and C, respectively). These scores were submitted to a repeated measurement ANOVA with the factors Attention (spatial attention vs intermodal attention), Hemisphere (contralateral vs ipsilateral) and Cluster (1–8). These post hoc topographical comparisons were conducted for the time window with the clearest separation between all four attention conditions, i.e. time window 125–175 ms for somatosensory ERPs.

As seen in Fig. 5, spatial attention and intermodal attention effects were differently distributed across hemispheres [Attention × Hemisphere $F_{(1,14)}=5.20$, $P=0.039$]. The intermodal attention effect was more lateralized than the spatial attention effect.

Auditory ERPs

ERPs to auditory stimuli started to differ around 100 ms after stimulus onset as a function of attention for spatial position and modality (see Fig. 7). ERPs were more negative to stimuli of the attended than of the unattended side (see Fig. 7B) and for stimuli of the attended modality than of the unattended modality (see Fig. 7C).

Time epoch 100–170 ms. The N100–170 to auditory stimuli of the attended side was more negative than to auditory stimuli of the unattended side. This was true for the attend tones condition (*thick lines* in Fig. 7A) and the attend touch condition (*thin lines* in Fig. 7A) [Spatial attention × Hemisphere × Cluster $F_{(7,98)}=4.88$, $P=0.020$]. The spatial attention effect was most pronounced at central and parietal clusters of the contralateral hemisphere (Spatial attention × Cluster $F_{(7,98)}=7.66$, $P<0.001$; for C2, C4, C5, and C7 $P<0.03$) and had a broad distribution over the ipsilateral hemisphere (main effect of Spatial attention $F_{(1,14)}=7.80$, $P=0.014$; see Fig. 8A).

There was no interaction between Spatial attention and Intermodal attention, suggesting that the spatial attention effect was similar irrespective of whether auditory stimuli were attended or not. This was confirmed in separate ANOVAs for the unimodal and crossmodal spatial attention effect. For the attend tones condition a significant Spatial attention × Cluster interaction [$F_{(7,98)}=3.96$, $P=0.026$] was obtained. The effect was reliable for several clusters of both hemispheres (C2, C4, C5, I1, I2, I3, I4, I5, I6, and I7, all $P<0.05$). For the attend touch condition the spatial attention effect was most pronounced over the contralateral hemisphere (Spatial attention × Hemisphere × Cluster interaction [$F_{(7,98)}=5.11$, $P=0.005$; contralateral: Spatial attention × Cluster $F_{(7,98)}=4.679$, $P=0.006$; ipsilateral: no effects of Spatial attention, all $P>0.3$]. Separate analyses for single clusters revealed a marginal significant spatial attention effect at cluster C5 ($P=0.083$).

The N100–170 to auditory stimuli was more negative when tones were attended than when touch was attended. This effect had a broader distribution over the contralateral hemisphere than the ipsilateral [Intermodal attention × Hemisphere $F_{(1,14)}=7.17$, $P=0.018$] and had a fronto-central maximum [Intermodal attention × Cluster $F_{(7,98)}=16.37$, $P<0.001$; see Fig. 8B]. Separate ANOVAs for hemispheres and clusters showed that the effect was reliable at most clusters of both hemispheres (for clusters C1, C2, C3, C4, C5, C6, I1, I2, I3, I4, and I5, all $P<0.05$).

Time epoch 200–350 ms. The N200–350 to auditory stimuli of the attended side was more negative than to stimuli of the unattended side but only when tones were

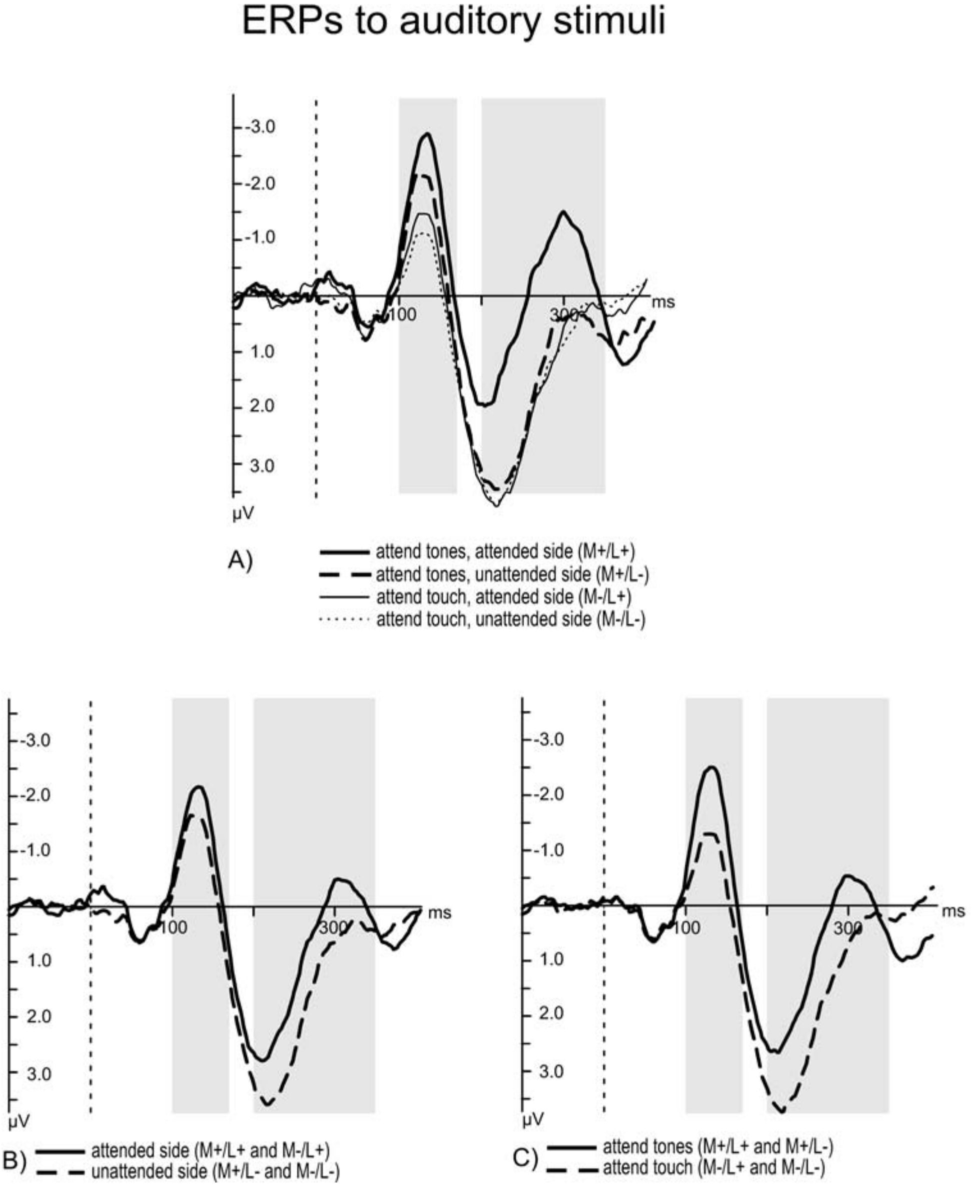

Fig. 7A–C Grand average event-related potentials (ERPs) to auditory standard stimuli at a contralateral central cluster (C5). **A** ERPs for all four attention conditions are superimposed. **B** ERPs to stimuli presented at the attended side (*solid lines*) versus unattended side (*dashed lines*) collapsed across intermodal attention conditions. **C** ERPs to stimuli when tones were attended (*solid lines*) versus when touch was attended (*dashed lines*) collapsed across spatial attention conditions. Time windows used in the statistical analyses are marked *gray*. Negativity is up

relevant [Spatial attention × Intermodal attention × Cluster $F_{(7,98)}=13.42$, $P<0.001$]. Separate ANOVAs for single clusters showed that the interaction between Spatial attention and Intermodal attention was significant for all clusters (all $P<0.05$). The unimodal spatial attention effect had a fronto-central maximum and was reliable for all clusters (all $P<0.04$).

The N200–350 to auditory stimuli was more negative when tones were attended than when touch was attended. This effect was more pronounced for stimuli of the attended side than for those of the unattended side (see above: Spatial attention × Intermodal attention × Cluster). The Intermodal attention effect for the attended side was significant for all clusters (all $P<0.03$) with a fronto-central maximum. The Intermodal attention effect for the unattended side was significant at frontal clusters of both hemispheres and at contralateral central clusters (for clusters C1, C2, C3, C4, and I1, all $P<0.04$).

Topography. An ANOVA with normalized difference amplitudes (attended side minus unattended side) as dependent variable for time epoch 100–170 ms showed no significant interaction with Intermodal attention, suggesting that there were no topographical differences between unimodal and crossmodal spatial attention effects (see Fig. 9).

Post hoc comparisons between the topography of Spatial attention and Intermodal attention effects for auditory ERPs were performed for time window 100–170 ms. There were significant topographical differences between spatial attention and intermodal attention effects [Attention × Hemisphere × Cluster $F_{(7,98)}=4.02$, $P=0.019$; see Fig. 8]. The spatial attention effect was maximal over centro-parietal electrodes contralateral to the side of stimulation while the intermodal attention effect had a fronto-central distribution.

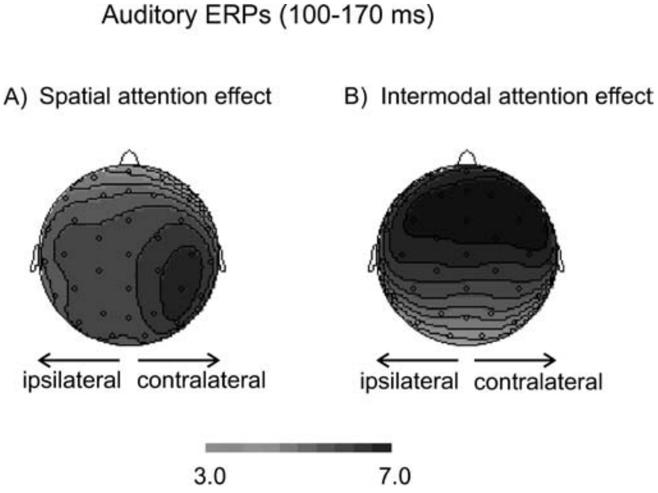

Fig. 8A,B Top view of the normalized topography (mean 5, SD 2) for auditory event-related potentials (ERPs) between 100 and 170 ms. **A** Spatial attention effect [(M+/L+ and M–/L+) minus (M+/L– and M–/L–)]. **B** Intermodal attention effect [(M+/L+ and M+/L–) minus (M–/L+ and M–/L–)]. Larger values (*darker shading*) indicate a relatively more negative amplitude

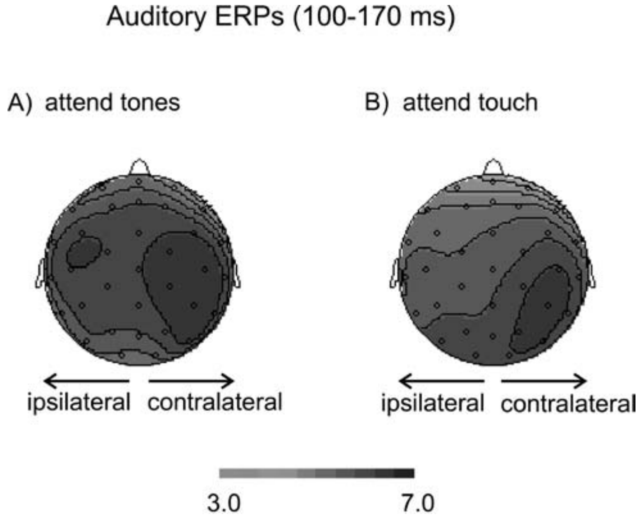

Fig. 9A,B Top view of the normalized topography (mean 5, SD 2) of the spatial attention effect for auditory event-related potentials (ERPs) between 100 and170 ms. **A** Attend tones condition (M+/L+ minus M+/L–). **B** Attend touch condition (M–/L+ minus M–/L–). Larger values (*darker shading*) indicate a relatively more negative amplitude

Discussion

The aim of the present study was to investigate effects of crossmodal and intermodal attention upon the processing of somatosensory and auditory stimuli. ERPs were recorded while randomized streams of auditory and tactile stimuli were presented from the left and right side. Participants had to attend to one modality at one spatial position only in order to detect rare deviant events of that modality at that position. In addition to unimodal spatial attention effects, crossmodal effects of spatial attention and intermodal attention effects were obtained.

Unimodal spatial attention

When touch was attended tactile stimuli of the attended side elicited an enhanced negativity compared to stimuli of the unattended side. This effect started around 70 ms, lasting until about 300 ms. The early attention effects were seen only at central and temporal electrodes contralateral to the side of stimulation. These electrodes are located above the primary and secondary somatosensory cortex (Allison et al. 1992). Attention effects after 200 ms were recorded over both hemispheres at central and temporo-parietal electrodes but were still more pronounced over the contralateral hemisphere. These results are in accordance with previous ERP studies on somatosensory attention showing a similarly enhanced negativity for attended stimuli (Eimer and Driver 2000; Eimer et al. 2001, 2002; García-Larrea et al. 1995; Michie 1984). In contrast to Michie et al. (1987), no positive modulations due to spatial attention were observed for somatosensory ERPs in the present study.

When tones were task-relevant, ERPs to auditory stimuli at the attended side showed enhanced negative amplitudes between 100 and 350 ms. The early part of this negativity had a central distribution more pronounced contralateral to stimulation, while the later part was maximal at fronto-central electrodes of both hemispheres. The attention effects for auditory ERPs were very similar to those described in earlier unimodal studies (e.g. Hansen and Hillyard 1980; Hillyard et al. 1973; Näätänen et al. 1981).

Crossmodal spatial attention

When participants directed their attention to a spatial position, task-irrelevant stimuli of the unattended modality presented at the attended position elicited more pronounced ERPs than when presented at an unattended position. Evidence for crossmodal spatial attention effects were found in ERPs peaking earlier than 200 ms although they were not as strong and as reliable as the unimodal spatial attention effects. This is in agreement with previous ERP studies on crossmodal spatial attention reporting less strong crossmodal than unimodal spatial attention effects (e.g. Eimer and Schröger 1998; Teder-Sälejärvi et al. 1999). Neither for somatosensory nor for auditory ERPs were such effects observed for time epochs later than 200 ms.

The present result pattern differs from that of Eimer et al. (2002) who did not find modulations of somatosensory ERPs when tones were task-relevant. In addition, in a visual-tactile experiment Eimer and Driver (2000) did not obtain any influence of visual spatial attention on somatosensory ERPs. Therefore, it was concluded that it might be possible to decouple the tactile modality from other modalities when totally task-irrelevant (Eimer and Driver 2000; Eimer et al. 2002). In their auditory-tactile study Eimer et al. (2002) used a cue at the beginning of each trial to indicate the spatial position to be attended whereas in our study the location to be attended remained constant throughout a block. Sustained and transient attention can affect ERPs differently (Eimer 1996); it might be that crossmodal links from hearing to touch are restricted to sustained attention situations.

An alternative explanation for the asymmetry of crossmodal effects in the studies of Eimer and co-workers could be that the discrimination difficulty between standards and targets differed between the modalities: tactile targets were detected faster than auditory (Eimer et al. 2002) or visual targets (Eimer and Driver 2000). One could argue that during the tactile task more resources were available to process stimuli of the unattended modality than during the auditory or visual task. In the present study, difficulty was matched across modalities, which could be a reason why evidence for a bi-directional crossmodal spatial attention effect was obtained.

ERPs are used in multimodal research because they have a high temporal resolution that allows to investigate at which processing stage input from different senses is integrated. Moreover, the topography of ERPs provides some evidence about the neural correlates of multisensory integration. Therefore, we compared the scalp topography of unimodal and crossmodal spatial attention effects. Both effects were maximal over modality-specific brain areas suggesting that unimodal and crossmodal attention affects early processing steps associated with sensory projection areas. As an underlying neural mechanism, feedback projections from multisensory representations of space to modality-specific areas have been suggested (Driver and Spence 2000; Macaluso et al. 2000).

Moreover, single-cell recordings in animals have detected multimodal neurons with overlapping receptive fields for visual, auditory, and tactile stimuli in the colliculus superior of cats and monkeys (Wallace et al. 1996, 1998), the anterior ectosylvian sulcus of the cat cortex (Wallace et al. 1992), and in the ventral premotor and temporo-parietal association cortex of the monkey (Graziano et al. 1999; Leinonen et al. 1980). Recordings from these neurons showed that responses to multimodal stimuli delivered from the same spatial position were enhanced compared with those to unimodal stimuli and the response rate to multimodal stimuli was higher than the sum of the unimodal response rates (Wallace et al. 1996, 1998). Spatial concordance of stimuli seems to be essential for their integration and therefore, it is not surprisingly that some multimodal neurons in animals responded to auditory stimuli only when they were presented near to the body surface (Graziano et al. 1999).

Furthermore, a case report from a patient suffering from auditory-tactile extinction showed corresponding results for humans: tactile stimuli presented on the contralesional side were extinguished when a tone was delivered on the ipsilesional side. However, this extinction was markedly reduced when the tone was presented far away from the head (Làdavas et al. 2001).

In sum, human electrophysiology, neuropsychology, and animal studies suggest that the brain integrates spatial congruent tactile and auditory input and that this integration starts as early as 100 ms after stimulus presentation.

Intermodal attention

When participants attend to one modality, ERPs to stimuli of that modality differ from those elicited when this modality is unattended. For somatosensory ERPs this intermodal attention effect is seen as a negative deflection contralateral to the side of stimulation, starting around 70 ms and lasting up to about 300 ms. At ipsilateral electrode sites there was no negative component between 70 and 100 ms, which is in agreement with earlier findings (Michie et al. 1987). Instead, ERPs to stimuli of the attended modality were more positive than those to unattended stimuli at ipsilateral electrodes. After 125 ms a broad negativity for the attended modality was seen over both hemispheres. The contralateral N70–100 could represent activity mainly in the primary somatosensory cortex while the later negativity may be generated in the secondary somatosensory cortex, which has a more bilateral organization (p 284 in Regan 1988).

The auditory ERPs when tones were relevant, compared with those when touch was relevant, showed an enhanced negativity starting at 100 ms and lasting until about 300 ms. The time-course of the modality attention effect is very similar to that of the unimodal spatial attention effect. Alho et al. (1992) and Woods et al. (1992) reported different results for intermodal attention: while in the N1 range, auditory stimuli showed an enhanced negativity when tones were attended compared to when visual stimuli were attended; in the P2 range an enhanced positivity was seen. In these studies, participants had to select stimuli of the attended modality along one dimension only (standard vs deviant). However, when the selection took place along two dimensions within the attended modality (e.g. left vs right, and standard vs deviant), the amplitude of ERPs to the auditory stimuli with the attended feature were more negative than those to auditory stimuli when vision was attended (Alho et al. 1994; Talsma and Kok 2001). Talsma and Kok (2001) argued that a more precise selection elicits a more pronounced processing negativity. Therefore, different task requirements may possibly account for some of the different findings between studies.

Selecting modality and spatial position

In the present study participants had to process stimuli by means of three features: modality, spatial position and continuity (gap or no gap). ERPs suggest that selection for spatial position and modality initially takes place in parallel. Stimuli with both attended features (M+/L+)

elicited the most pronounced negativity, ERPs to those matching only one attended feature (M+/L– or M–/L+) were more negative than those to stimuli that did not match any feature at all (M–/L–). According to Näätänen (1982), the attention-related negativity ("processing negativity") indicates comparisons between an incoming stimulus and an internal representation of the stimuli to be attended. The magnitude and duration of the processing negativity is proposed to reflect the similarity between the actual stimuli and the internal representation of the stimuli to be attended.

We also observed a difference between ERPs to the M+/L– stimuli and the M–/L+ stimuli with the former being more negative. As modality might be easier to discriminate than spatial position, stimuli matching only the modality feature elicited more negative ERPs than those matching only in spatial position. By 200 ms, stimuli of the unattended modality seem to have been rejected from further processing as there is no longer any effect of spatial position for the irrelevant modality. The increasing difference between attended and unattended side for the attended modality at later latencies suggests that only the stimuli matching both relevant features are processed further.

The time-courses of the spatial attention effect and the modality attention effect are very similar. However, a post hoc comparison between the topography of these effects showed that they differed. These results suggest that selection for spatial position and modality may be mediated in part by non-identical neural systems. In a recent positron emission tomography study, Macaluso et al. (2002) showed that different brain regions were activated by selectively attending spatial locations and modality. Spatial attention modulated activity in early modality specific regions only (e.g. contralateral somatosensory cortex for tactile stimuli), while intermodal attention effects were observed in early sensory as well as in higher-order parietal areas. In the latter a different activation pattern for attending visual versus tactile stimuli was observed. It is suggested that modality-specific control processes within parietal areas bias the spatial processing within sensory areas via top-down mechanisms. In agreement with this brain imaging data, in the present study the topography of the spatial attention effect was maximal over sensory areas too (over somatosensory cortex for tactile stimuli and over contralateral central areas for auditory stimuli). Moreover, the intermodal attention effects had a broader distribution. The intermodal attention effect was maximal over frontal areas for auditory ERPs, and there seemed to be a tendency towards a more frontal topography for somatosensory ERPs as well (see Fig. 5B). Frontal brain regions are known to be important for the top-down control of attention (LaBerge 2000), and for multisensory processing (Downar et al. 2000; Giard and Peronnet 1999; Luo and Wei 1999). It could be speculated that frontal mechanisms for selecting modality and the mechanism for selecting spatial position within sensory areas are initially active in parallel. Later on, top-down connections between higher-order areas and sensory-specific areas restrict spatial processing to the relevant modality. The pattern of results is in accordance with hierarchical models of selective attention (Hansen and Hillyard 1983). Further studies will uncover the precise functional architecture of these processes.

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