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RESEARCH ARTICLE

Spatial attention affects the processing of tactile and visual stimuli presented at the tip of a tool: an event-related potential study

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Abstract An event-related potential (ERP) experiment was conducted in order to investigate the nature of any cross-modal links in spatial attention during tool use. Tactile stimuli were delivered from the tip of two sticks, held in either a crossed or an uncrossed tools posture, while visual stimuli were presented along the length of each tool. Participants had to detect tactile deviant stimuli at the end of one stick while trying to ignore all other stimuli. Reliable ERP spatial attention effects to tactile stimuli were observed at early (160–180 ms) and later time epochs (>350 ms) when the tools were uncrossed. Reliable ERP attention effects to visual stimuli presented close to the tip of the tool and close to the hand were also observed in the uncrossed tools condition (time epoch 140–180 ms). These results are consistent with the claim that tool-use results in a shift of visuospatial attention toward the tip of the tool and also to attention being focused by the hand where the touch is felt.

Keywords Tool-use · Peripersonal space · Cross-modal attention · Vision · Touch

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Introduction

When attention is directed to a particular location where task-relevant events happen to be presented within one (primary) sensory modality, target performance is also enhanced when stimuli are presented in another (secondary) modality at the same location as well (e.g. Driver and Spence 2004; Eimer and Driver 2000; Giard and Peronnet 1999). Event-related potential (ERP) studies have provided evidence that cross-modal links in spatial attention exist at early, sensory-related processing stages, starting around 100 ms post stimulus-onset or even earlier (see Hillyard et al. 1984; Eimer 2001). When stimuli are presented at attended locations, they evoke enhanced ERPs as compared to situations in which the same stimuli are presented at an unattended location (or side), irrespective of whether they belong to the task-relevant modality (unimodal spatial attentional effect), or to the currently task-irrelevant modality (cross-modal spatial attentional effect; Eimer et al. 2001; Hötting et al. 2003).

Cross-modal links in spatial attention have now been extensively studied for both endogenous (voluntary) and exogenous (involuntary) spatial attention (see Driver and Spence 2004; Eimer and van Velzen 2005; Spence et al. 2004). For instance, Kennett et al. (2001) used an exogenous spatial cueing paradigm, in which spatially non-predictive tactile cues were presented to the hand, shortly before to the visual targets. They found that the visual N1 was enhanced when tactile stimulation was presented from the same rather than from a different location to a visual target event. Meanwhile, other researchers have also provided evidence for the existence of cross-modal links in endogenous spatial attention between vision and touch (e.g. Eimer and Driver 2000; Spence et al. 2000). For example, the participants in a study by Eimer and Driver had to detect tactile or visual targets on the attended side and had to ignore the irrelevant modality and stimuli on the unattended side. They found effects of endogenous spatial attention for visual ERPs when touch was the task-relevant modality but not vice versa. In general, the ERP spatial attention effects were always smaller in the task-irrelevant or secondary modality than in the primary modality. Taken together, results of these studies therefore provide a growing body of evidence in support of the existence of cross-modal links in spatial attention between vision and touch. Given that at the earliest stages of information processing, spatial representations are highly modality-specific (retinotopic in vision, somatotopic in touch, head-centered in audition), researchers have frequently argued about the characteristics of the spatial representations that are used for cross-modal binding of spatial information.

For the case of visual–tactile interactions, two main hypotheses have been put forward to explain the existing data. According to the hemispheric-activation account, visual and tactile stimuli on the same side of space will typically project initially to the same hemisphere (anatomical spatial codes), resulting in cross-modal attentional effects or processing advantages for spatially congruent stimuli. According to an alternative hypothesis, cross-modal links in spatial attention are based on representations of common locations in external space (external spatial codes). Normally, researchers have attempted to distinguish between these two hypotheses simply by changing the posture of the tactually stimulated limbs. The latter account predicts that attending to the left hand leads to attentional benefits on the left side of visual space with uncrossed hands, but to benefits for the right visual space when hands are crossed. By contrast, if crossmodal links depend on a reference frame that is anchored on anatomical coordinates, the position of the hand is expected to be irrelevant: that is, attending to the left hand always enhances the processing of visual stimuli in the left hemifield irrespective of where the hand is located. When a participant's hands are placed in an uncrossed posture, the external and anatomical spatial codes for tactile stimuli at the left and right hand are congruent, whereas in the crossed hands posture they are incongruent. Both processing speed and accuracy have been found to decrease in the crossed hands condition as compared to the uncrossed hands condition, suggesting that tactile inputs are by default remapped into external coordinates (Schicke and Röder 2006; Shore et al. 2002; Yamamoto and Kitazawa 2001a, as well). Since congenitally blind participants appear to be completely unaffected by the crossing of their hands in the tactile temporal order judgment (TOJ) task, it has been suggested that the default use of an external reference frame for tactile localization is visually induced (Röder et al. 2004).

Eimer et al. (2001) used ERPs in order to investigate cross-modal links between vision and touch both when participants adopted an uncrossed and when they adopted a crossed hands posture. Participants directed spatial attention to the left or right hemifield in order to detect infrequent tactile deviant stimuli in the attended hemifield. ERP cross-modal attention effects for the visual probes delivered near the hands were very similar for both postures, except that they were delayed and reduced in amplitude in the crossed hands condition. These findings therefore suggest that tactile stimuli that are applied directly to the hands are remapped into an external frame of reference.

It has been suggested that tool use extends the visuotactile representation of peripersonal space (Berti and Frassinetti 2000; Farne et al. 2005; Iriki et al. 1996; Maravita et al. 2001). When holding tools in a crossed posture, performance has been shown to deteriorate in a similar manner as when the hands are crossed. Similarly, performance also worsens quite markedly when the stimuli are delivered to the tips of tools when hands instead of tools are crossed (Yamamoto and Kitazawa 2001b). With the crossed tools, the tip of the tool held with the right hand is located in left visual space, and the tip of the tool held in the left hand is located in right visual space, while the position of the hands is the same in both the crossed and the uncrossed posture conditions. A conflict between an anatomically and an external frame of reference is expected if tactile stimuli are represented according to their origin in external space.

The present study investigated the spatial coordinate systems used for locating tactile stimuli delivered to the tips of two sticks (tools). Moreover, we used ERPs to characterize the spatial distribution of visual attention in the space around the lengths of the sticks. Visual stimuli (LEDs) were delivered in a random order to the tips of tools, near the hands, and in the middle of the shafts of two tools which were held in the hands. Participants were engaged in a tactile oddball task. They had to attend to the left or the right side of external space, and had to detect deviant tactile stimuli delivered at the tip of one tool while ignoring all frequent stimuli at this tool as well as all tactile stimuli presented to the tip of the other tool. When tactile stimuli were delivered at the tip of the tools, we expected to see a similar attention effect on ERPs as have previously been observed for tactile stimuli present directly to the hand (an enhancement of the N80 and the N1). Holmes et al. (2004) results suggest that visual–tactile interactions may only emerge around the proximal and distal tips of the tools. Cross-modal effects of spatial attention from touch to vision were thus mainly expected for LEDs at these locations.

Method

Participants

This study was conducted at the University of Hamburg (Germany). Fifteen undergraduate students took part in the experiment. One participant had to be excluded due to poor behavioral performance (failing to detect more than 60% of the targets). The data from the remaining 14 participants (8 females, aged 21–39 years; average age: 28.2 years) were analyzed. All of the participants had normal or corrected-to-normal vision, normal hearing, and normal tactile sensitivity by self-report. The participants received course credits or were paid 7 Euro per hour for taking part in the study. The participants all gave their informed consent before taking part in the experiment.

Stimuli and design

Two tactile stimulators (Oticon bone conductor BC461-0/12, Oticon Ltd., London, UK) were attached to the tips of the tools (wooden sticks, 1.3 cm in diameter, and 40 cm in length). The tactile stimuli consisted of 167 Hz vibrations. The standard tactile stimulus was presented for 200 ms. The tactile deviants (25% of all tactile stimuli) were presented for 200 ms as well, but they included a 10 ms gap 95 ms after stimulus onset. The faint noise associated with the operation of the tactile stimulators was masked by white noise presented from two loudspeaker cones located on the center of the table. Light emitting diodes (LEDs) were used to present the visual stimuli (duration: 200 ms). Four LEDs were mounted on each tool (see Fig. 1): One at the tip of each tool, one near the participant's hand, and two spaced equally along the shaft of a tool (one closer to the tip, the other nearer to the hand).

Procedure

Participants sat in a dimly lit experimental chamber. They had to put their chin on a chin-rest, and had to maintain central fixation throughout each block of trials.

There were four task conditions: (1) attend to the tactile stimuli presented in the left hemifield; tools uncrossed; (2) attend to the tactile stimuli presented in the right hemifield; tools uncrossed; (3) attend to the tactile stimuli presented in the left hemifield; tools crossed; (4) attend to the tactile stimuli presented in the right hemifield; tools crossed. The visual stimuli (60% of all stimuli) and the tactile stimuli (40% of all stimuli; 75% of the tactile stimuli were standards, and 25% were deviants) were presented in a random order. Four experimental blocks of 360 trials were presented for each task condition. The average inter-trial interval (ITI) was 500 ms (varying randomly between 400 and 600 ms). The order of presentation of the four conditions was counterbalanced across participants using a Latin-square design. At least two practice runs were completed prior to the main experimental blocks, one with the sticks crossed, the other with the sticks uncrossed. The participants were given the opportunity to take a break after the completion of each block of trials.

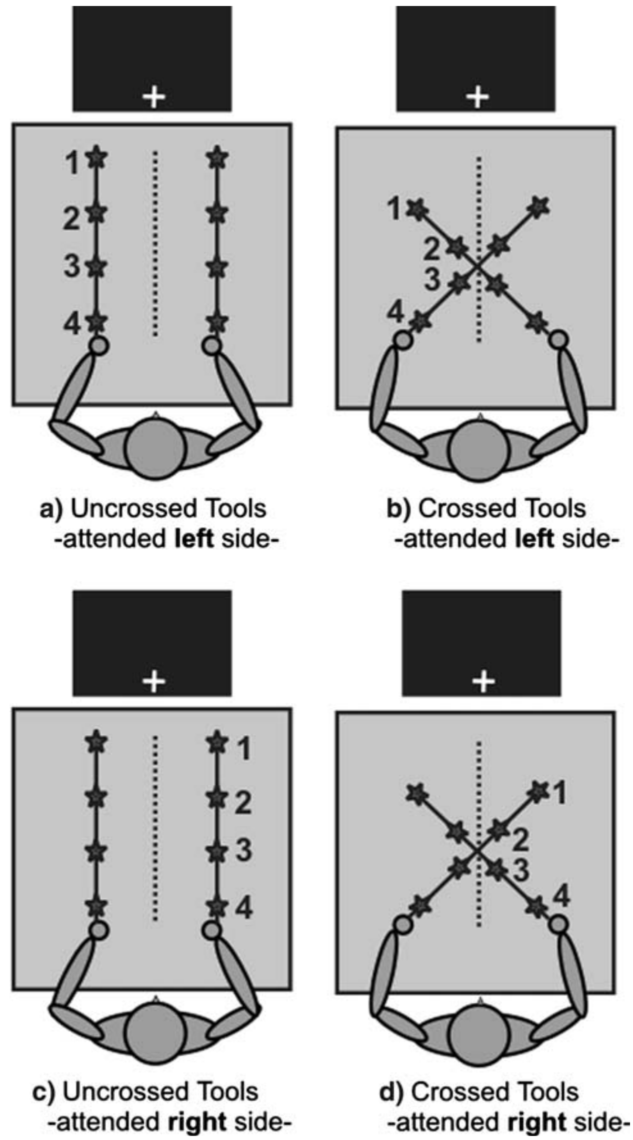

Fig. 1 Participants held one tool in either hand. Visual probes (the *stars* in the figure) were presented at the tips of the tools (location 1), in the middle of the shafts (locations 2 and 3), or close to the participant's hands (location 4). The tactile stimuli were always presented from the tips of the tools. The locations of visual probes at the attended side are marked

Instructions specifying the tool posture and the attended hemifield were displayed on a computer screen prior to the start of a block. The participants were instructed to respond to deviant tactile stimuli (double tactile stimuli) presented in the attended hemifield by lifting the foot pedal. All other stimuli had to be ignored (i.e., tactile standard stimuli in the attended hemifield, and visual stimuli on both sides). They were instructed to respond to target stimuli as rapidly and as accurately as possible within a time epoch of 2000 ms following target onset. A white fixation cross (1° × 1° of visual angle) was presented on the black computer screen positioned 60 cm from the participants throughout each block of trials.

Previous research has shown that active tool-use is often a prerequisite for coding tools as being located in peripersonal space (see Maravita et al. 2002). In the present study, a movement task was introduced that required the participants to actively use the tools. Tones (600 Hz, 100 ms) were occasionally (one to four times) delivered over headphones during a block of trials. The participants were instructed to move the tip of the stick to the left when a tone was presented to their left ear and to the right when a tone was presented to their right ear. They were instructed to move the tip of the stick that was located in the same hemifield as the tone. Thus, when the tools were crossed, the tip of the tool held in the left hand had to be moved to the right after a right tone, and the tip of the tool held in the right hand had to be moved to the left after a left tone.

ERP recording

ERPs were recorded from 61 scalp Ag–AgCl electrodes mounted into an elastic cap (Easy Cap; FMS, Herrsching–Breitbrunn, Germany). All of the scalp electrodes were referred to an electrode attached to the right earlobe. A linked earlobe reference was calculated offline.

Vertical eye movements were monitored (electrooculogram, EOG) with an electrode mounted 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 both the scalp and eye electrodes. All of the recordings were amplified with a band pass of 0.01–100 Hz. The digitization rate was 500 Hz.

Data analyses

The experiment involved a 2×2 within-participants design with the factors of Attention (attended vs. unattended side; defined with respect to the midline of the body) and Tool Posture (uncrossed vs. crossed).

Behavioral data

For the behavioral data, hits, misses, and false alarms were calculated separately for each condition allowing us to derive d’ ($z(p(\text{hit})) - z(p(\text{false alarm}))$) (Green and Swets 1966). Reaction times (RTs) to the deviant stimuli were calculated from the onset of the gap (95 ms after the onset of the stimulus). Only RTs below 1,500 ms from correct hit responses were included. Analyses of variance (ANOVAs) were calculated separately for the RTs and for d' with the within-participant factors of Attended Side (left vs. right) and Tool Posture (uncrossed vs. crossed).

EEG data

Somatosensory and visual ERPs to standard stimuli (non-target stimuli) were averaged separately for each participant and each condition. Visual ERPs were calculated separately for each LED position. The EEG and the EOG were epoched offline into 800 ms time intervals, starting 100 ms prior to, and ending 700 ms after the onset of a stimulus. ERPs to attended and unattended stimuli were separately pooled over the left and right side. For tactile stimuli, electrodes were remapped to ipsilateral and contralateral recording sites with respect to the hand receiving the vibration. For visual stimuli, electrodes were remapped to ipsilateral and contralateral recording sites with respect to the hemifield of stimulation (see Fig. 1). Electrodes were clustered: An average ERP was calculated for the three electrodes comprising each cluster. The clusters were named relative to the side of stimulation as ipsilateral (I) and contralateral (C) and numbered from 1 to 8 according to their location along the anterior–posterior axis. A schematic drawing of electrode montage is presented at the bottom of Figure 2. Fz, Cz, Pz, and Oz according to the 10–20 system are marked in the schematic drawing of the electrode montage.

Trials with eye movement artifacts (HEOG and VEOG exceeding ±100 μV relative to baseline) and with other artifacts (a voltage exceeding ±150 μV at any electrode location relative to baseline) were eliminated. If there was a response in the analyzed time epoch following a standard stimulus (up to 900 ms poststimulus), this trial was not included in the average.

For the statistical analyses, mean amplitudes were calculated for the selected time windows: For somatosensory ERPs: (1) 75–90 ms (N80), (2) 160–180 ms (N1), (3) 230–300 ms, and (4) 350–500 ms; for visual ERPs: 140–180 ms (N1). Time epochs were defined on the basis of the results of earlier studies (see Eimer et al. 2001; Hötting et al. 2003) and on a visual inspection of the group grand average ERPs.

Results

Behavioral performance

Participants missed 10.3% (SE 0.2%) of the target stimuli (tactile deviants) in the uncrossed tools condition, as compared to 10.3% (SE 1.6%) in the crossed tools conditions. Participants made 1.2% false alarm responses (SE 0.4%) in the uncrossed tools condition, and 1.8% (SE 0.3%) false

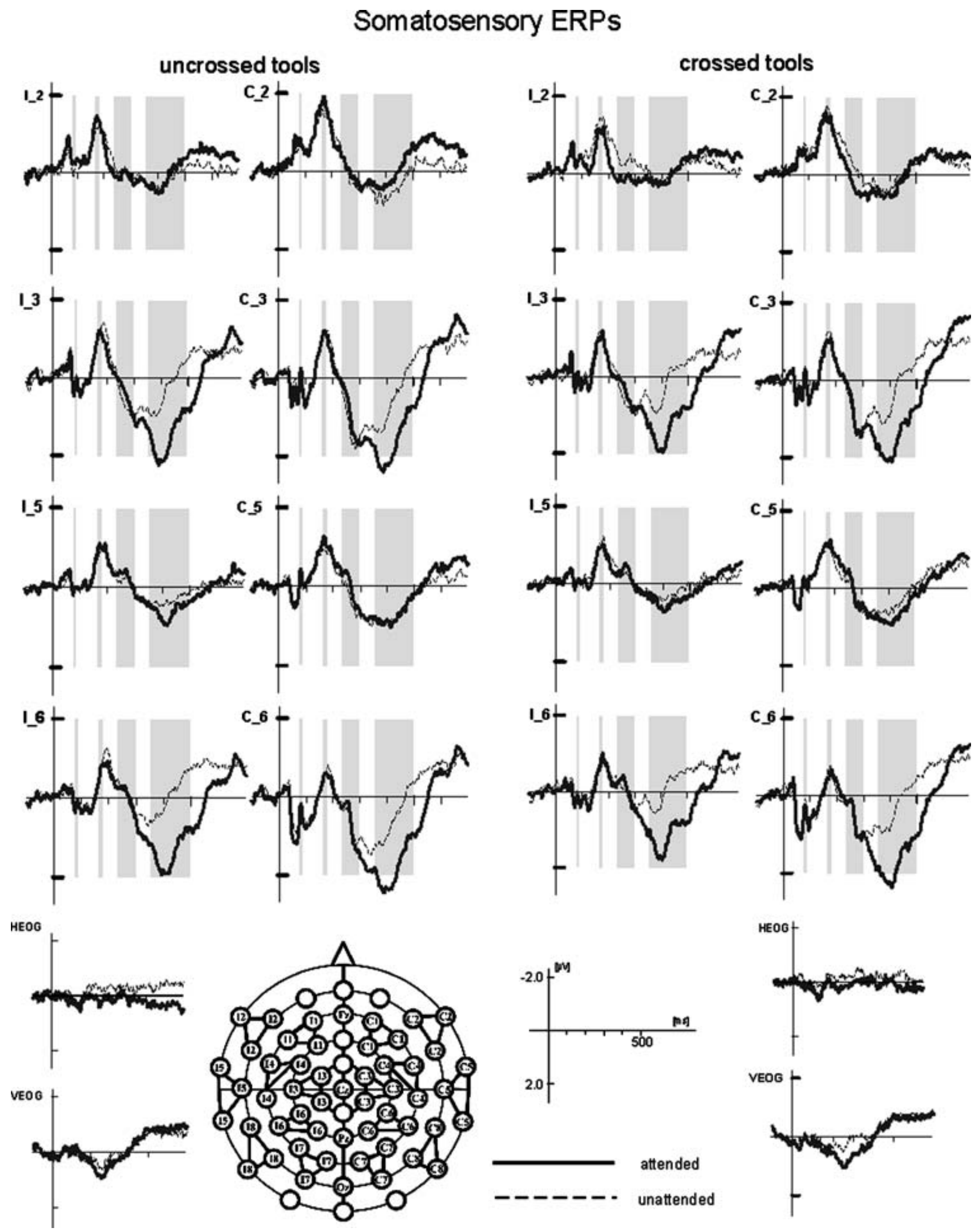

Fig. 2 Grand-averaged somatosensory ERPs elicited by tactile stimuli at the attended versus unattended location where tactile stimuli were presented (*solid* vs. *dashed lines*). All waves represent the mean signal of three electrodes (see the *lower panel*). ERPs are displayed separately for the uncrossed tools condition (*left*) and the crossed tools condition (*right*). Time windows used in the statistical analyses are marked in *grey*

alarm responses in crossed tools condition. Tool Posture did not have any significant effect on number of hits, misses, or false alarms. The mean d' value was 3.78 (SE 0.21) for uncrossed tools condition and 3.72 (SE 0.17) for crossed tools condition.

The mean RTs were shorter in the uncrossed (692 ms, SE 34.7 ms) than in the crossed tools condition (712 ms, SE 38.5 ms), t (13) = 2.2, $P < 0.05$.

ERP results

Attentional modulations of somatosensory ERPs

The mean amplitudes of the four epochs were analyzed separately for somatosensory ERPs using a repeated measures ANOVA with the following factors: Attention (attended vs. unattended), Tool Posture (crossed vs. uncrossed), Hemisphere (contralateral vs. ipsilateral to the hand) and Cluster (electrode cluster 1–8). The results of the ANOVA conducted at each time epoch are reported in Table 1. The most important finding to emerge from this analysis was the significant three-way interaction of Attention × Tool posture × Cluster. This effect was further analyzed in subordinate ANOVAs.

Figure 2 shows the grand average of the somatosensory ERPs elicited at the contralateral and ipsilateral electrode clusters (with respect to the stimulated hand) for attended (solid lines) vs. unattended (dashed lines) tactile stimuli. ERPs are shown separately for the uncrossed and crossed tools conditions.

Table 1 Results of the ANOVA conducted on the somatosensory ERP data in each time epoch

Tactile stimuli	Time epoch			
	75–90 ms	160–180 ms	230–300 ms	350–500 ms
Attention				9.6 ($P < 0.01$)
Cluster	9.3 ($P < 0.01$)	14.0 ($P < 0.01$)	3.3 ($P < 0.01$)	3.6 ($P < 0.01$)
Attention × Cluster		2.2 ($P < 0.05$)	2.7 ($P < 0.05$)	11.7 ($P < 0.01$)
Attention × Hemisphere				6.9 ($P < 0.05$)
Cluster × Hemisphere	2.5 ($P < 0.05$)			2.4 ($P < 0.05$)
Tool posture × Hemisphere	5.2 ($P < 0.05$)		21.2 ($P < 0.01$)	9.5 ($P < 0.01$)
Attention × Tool posture × Cluster		4.0 ($P < 0.01$)	3.0 ($P < 0.01$)	
Tool posture × Hemisphere × Cluster	32.0 ($P < 0.01$)	15.3 ($P < 0.01$)	31.4 ($P < 0.01$)	6.9 ($P < 0.01$)

F value and *P* value (in parentheses)

75–90 ms time epoch: None of the interactions involving Attention were significant in either the uncrossed or crossed tools conditions. The four-way ANOVA revealed a significant Tool Posture by Hemisphere by Cluster interaction, $F(7, 91) = 32.0$, $P < 0.001$.

160–180 ms time epoch: The four-way ANOVA revealed a significant Attention by Tool Posture by Cluster interaction, $F(7, 91) = 4.0$, $P < 0.01$. ERPs were more negative in response to stimuli presented on the attended side than to stimuli presented on the unattended side (see Figs. 2, 3a). This effect was only reliable for the uncrossed tools condition. These observations were confirmed by statistical analyses. For the uncrossed tools condition, the three-way ANOVA (Attention × Hemisphere × Cluster) revealed a significant Attention by Cluster interaction, $F(7, 91) = 4.7$, $P < 0.001$. Subsequent *t*-tests showed that Attention resulted in significant amplitude differences at the fronto-lateral clusters (C2 and C5, one-tailed, $P < 0.05$).

230–300 ms time epoch: The four-way ANOVA revealed a significant Attention by Tool Posture by Cluster interaction, $F(7, 91) = 3.0$, $P < 0.01$, reflecting a larger attention effect at electrode sites located contralateral to the stimulated hand. This interaction was attributable to there being a more positive potential for the attended than for the unattended condition in the crossed tools condition (see Fig. 3b). Moreover, there was also a significant Tool Posture by Hemisphere by Cluster interaction, $F(7, 91) = 31.4$, $P < 0.001$. Follow-up ANOVAs showed a significant interaction between Attention and Cluster in the crossed tools condition, $F(7, 91) = 4.2$, $P < 0.001$, but not for the uncrossed condition. The results of subsequent *t*-tests on the single clusters revealed significant positive differences between attended versus unattended tactile locations at frontal lateral clusters in both hemispheres for the crossed tools posture (C2 and I2, both $P < 0.05$).

350–500 ms time epoch: The ANOVA revealed a highly significant main effect of Attention, $F(1, 13) = 9.6$, $P < 0.01$, as well as a significant interaction between Attention and Hemisphere, $F(1, 13) = 6.9$, $P < 0.05$, and a significant Attention by Cluster interaction, $F(7, 91) = 11.7$, $P < 0.001$, indicating that the effect of attention was larger over the contralateral hemisphere than over the ipsilateral

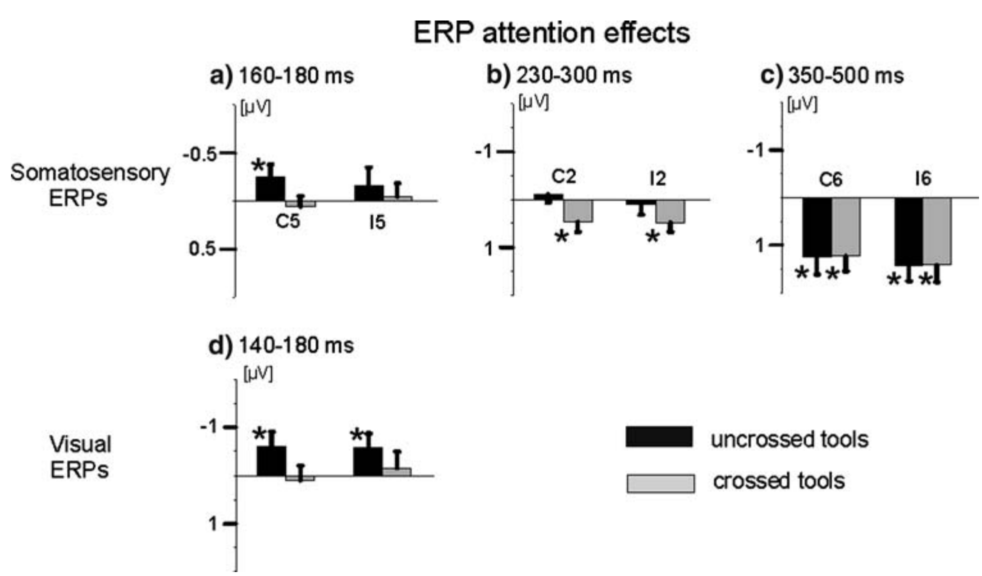

Fig. 3 Mean difference amplitudes (ERP attended–ERP unattended) for the somatosensory ERPs for time epochs: **a** 160–180 ms; **b** 230–300 ms; **c** 350–500 ms, and for the visual ERPs elicited by the LEDs attached to the tip of the sticks for the time epoch: **d** 140–180 ms. Significant ERP attention effects are marked (**$P < 0.01$, *$P < 0.05$). *Error bars* indicate the standard error of the mean. Note the different scales for **a** versus **b** and **c**

hemisphere. ERPs to attended tactile stimuli were significantly more positive than ERPs to unattended tactile stimuli. There was no interaction between Attention and Tool Posture in this time window, indicating that the effects of attention did not differ between the two tool postures (see Fig. 3c). In the uncrossed tools condition, the three-way ANOVA (Attention × Hemisphere × Cluster) revealed a significant interaction between Attention and Cluster, $F\,(7, 91) = 11.9$, $P < 0.001$. Subsequent t-tests showed that Attention resulted in a reliable positivity for the uncrossed condition at the following clusters (C2, C3, C6, C7, C8, all $P < 0.05$; I3, I4, I6, I7, I8, all $P < 0.05$). In the crossed tools condition, the three-way ANOVA (Attention × Hemisphere × Cluster) also revealed a significant interaction between Attention and Cluster, $F\,(7, 91) = 8.1$, $P < 0.001$. Subsequent t-tests showed that Attention resulted in a reliable positivity at the following clusters (C3, C6, C7, C8, all $P < 0.05$, C4, $P < 0.06$; I3, I6, I7, I8, all $P < 0.05$, I4, $P < 0.06$).

Visual ERPs

Mean amplitudes were analyzed for visual ERPs with a repeated measures ANOVA comprising five factors: Attention (attended vs. unattended), Tool Posture (crossed vs. uncrossed), Location (4 positions along the tool), Hemisphere (contralateral vs. ipsilateral to the side of stimulation) and Cluster (electrode cluster 1–8).

140–180 ms time epoch: The five-way ANOVA revealed a significant Attention by Tool Posture by Location by Hemisphere interaction, $F\,(3, 39) = 4.0$, $P < 0.05$ (see Table 2). Moreover, a significant Location by Hemisphere by Cluster interaction, $F\,(21, 273) = 7.0$, $P < 0.001$, suggested that the N1 attentional modulation was different for the four visual stimulus positions distributed along the length of the tools. The four-way ANOVAs (with the factors of Attention, Tool Posture, Hemisphere, and Cluster) were conducted separately for the four visual stimulus locations.

For the LEDs mounted at the tips of the tools, the four-way ANOVA revealed a marginally significant interaction between Attention and Tool Posture, $F(1, 13) = 3.4$, $P < 0.08$, as well as a significant Attention by Hemisphere by Cluster interaction, $F(7, 91) = 2.9$, $P < 0.01$. Follow-up ANOVAs obtained a significant Attention by Hemisphere by Cluster interaction for the uncrossed tools condition, $F(7, 91) = 2.6$, $P < 0.05$, but not for the crossed tools condition (see Fig. 4). Subsequent t-tests revealed a significant ERP attention effect in the uncrossed tools condition at central and occipital clusters (C1, C3, C4, C6, I3, I6, I7, one-tailed, all $P < 0.05$) (see Fig. 3d). For the LEDs near to the hands, the four-way ANOVA revealed a significant interaction between Attention, Tool Posture, and Cluster, $F(1, 13) = 6.7$, $P < 0.05$. Follow-up ANOVAs revealed a marginally significant interaction between Attention and Hemisphere in the uncrossed tools condition, $F(1, 13) = 3.8$, $P < 0.08$. Subsequent t-tests highlighted a marginally significant attentional modulation of the ERP in the uncrossed tools condition at frontal lateral cluster (I2, $P < 0.07$). By contrast, attention did not modulate visual ERPs in the crossed tools condition. For the visual LEDs presented along the shafts of the tools, none of the interactions involving Attention were significant in either the uncrossed or crossed tools conditions.

Table 2 Results of the ANOVA conducted on the visual ERP data

Visual stimuli	Time epoch 140–180 ms
Location	4.4 ($P < 0.01$)
Hemisphere	4.7 ($P < 0.05$)
Cluster	9.2 ($P < 0.01$)
Location × Cluster	3.8 ($P < 0.01$)
Location × Hemisphere	6.5 ($P < 0.01$)
Cluster × Hemisphere	2.4 ($P < 0.05$)
Location × Hemisphere × Cluster	7.0 ($P < 0.01$)
Attention × Tool posture × Location × Hemisphere	4.0 ($P < 0.05$)

F value and P value (in parentheses)

Discussion

ERPs were used in the present study to investigate selective spatial attention effects for tactile stimuli delivered to the tips of hand-held tools. Furthermore, we also analyzed the distribution of visual spatial attention along the length of the tools. Our results provide the first empirical evidence that ERPs to tactile stimuli presented at the tips of tools are modulated by spatial attention. Reliable spatial attention ERP effects to tactile stimuli were observed in both earlier (160–180 ms) and later (350–500 ms) time windows in the uncrossed tools condition. Similarly, we observed reliable ERP attention effects to visual stimuli presented at the tips of the tools and to visual stimuli presented from close to the participants' hands holding the tools. These crossmodal attention effects were, however, only reliably observed in the uncrossed tools condition.

Unimodal effects

In the experiment reported here, tool posture significantly impacted on attentional effects for the earlier somatosensory ERPs. This somatosensory N1 was enhanced for tactile stimuli presented at attended locations in the uncrossed

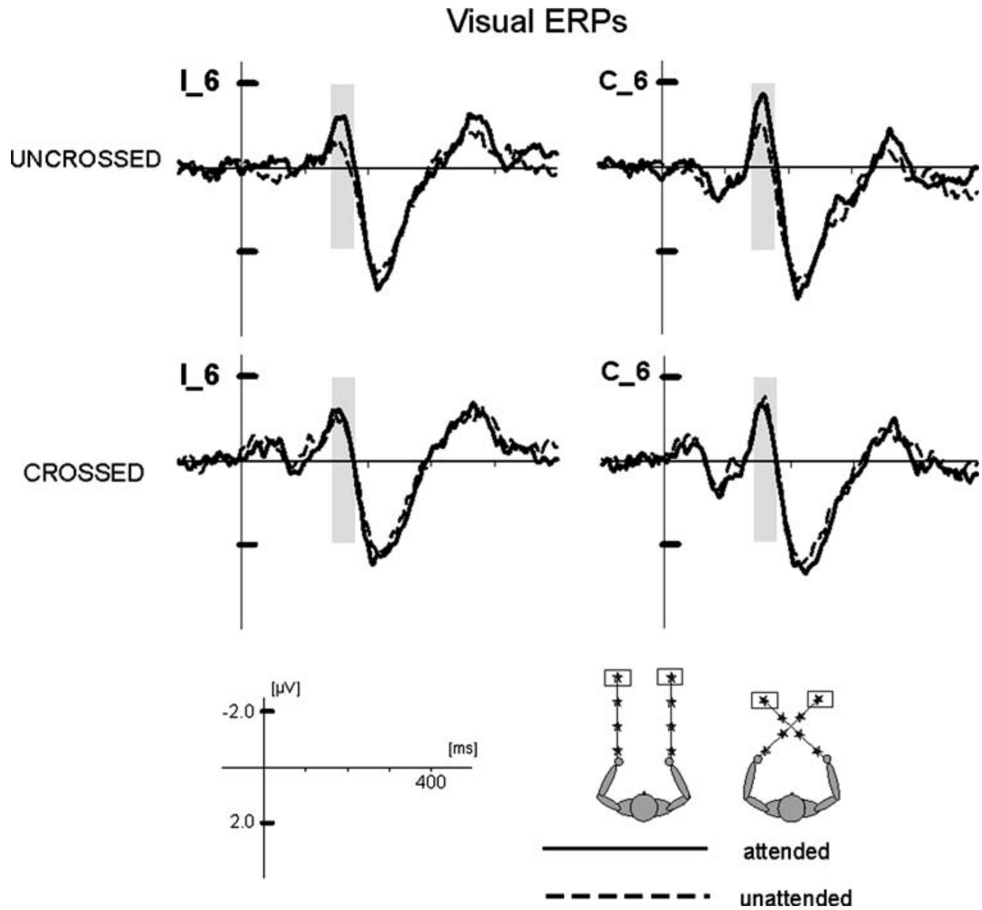

Fig. 4 Grand-averaged ERPs to visual stimuli elicited by the LEDs presented at the tip of the sticks at the attended vs. unattended side (*solid* vs. *dashed lines*). Waves are shown from 100 ms pre- to 500 ms post-stimulus onset. All of the waves represent the mean signal of a cluster of electrodes as depicted at the bottom of Fig. 2

tools condition. By contrast, no such effect was observed in the crossed tools condition. These results therefore suggest that the crossed tools posture disrupted early attention effects within the tactile modality. However, later enhanced attentional positivities (starting at around 300 ms after stimulus onset) to tactile stimuli were observed. Researchers have suggested that when the locations of the tip of the tool and hand do not fall into the same hemifield, the brain computes the position of hands in space based on different reference frames (Holmes and Spence 2004, 2006), including both an anatomical reference system and an external reference system. In the present study, the incongruency between the location of the tip of the tool and the hand might have resulted in the longer RTs observed for detecting the deviant stimuli in the crossed tools condition. The more difficult remapping process in the crossed tools condition might have resulted in the lack of any attentional modulation of the earlier somatosensory ERPs in the crossed tools condition. Interestingly, the pattern of somatosensory ERPs for the earlier time epochs in the crossed tools condition by-and-large resembled what has been reported under conditions where participants have crossed their hands (see Eimer et al. 2001; Röder et al. 2008). Furthermore, when the tools were crossed, participants had to direct their attention to the hand, which was located contralateral to the tactile stimulator. Thus attentional "resources" had to be distributed across two hemifields in the crossed tools condition.

One might legitimately wonder why we did not observe ERP attention effects at latencies earlier than 100 ms in either of the posture conditions. It should be noted that ERP attention effects in time epochs prior to 100 ms poststimulus tend to be less robust than later ERP attention effects. Specifically, these early effects seem to depend on the specific paradigm used. Due to the transfer of the vibration through the stick, the tactile stimulation reaching the hand was more sluggish than a vibration to the hand itself. This might have reduced the signal to noise ratio necessary to see earlier attention effects on somatosensory ERPs.

Crossmodal effects

An enhanced attention negativity in the uncrossed condition for ERPs elicited by visual stimuli presented at the tips of sticks was observed, i.e., at the location where the task-relevant tactile stimuli were presented. Moreover, a marginally significant cross-modal attentional modulation was also observed in the uncrossed tools condition for the LEDs situated closest to the hands as well. These earlier N1 attention effects were absent for visual stimuli presented along the shafts of the tools. Holmes et al. (2004) required participants to discriminate the elevation of vibrotactile stimuli presented to either their thumb (‘upper’) or forefinger (‘lower’) of either hand, while trying to ignore random, irrelevant visual distractors presented in either an upper or lower location. Participants performed this task in different tool-use conditions, with uncrossed tools. Holmes et al. (2004) observed visual–tactile interactions for these locations at the tool that was important for performing an action. Moreover, they always observed visual–tactile interactions for the hand holding the tool. Thus, the present study provides support for the claim that tool use is accompanied by very specific shifts of visual spatial attention. Our data suggest that tool-use results in a shift of visual attention toward the tip of the tools where the tactile stimuli were delivered and also to attention being focused by the hand where the vibration was detected.

The different cross-modal attention effects observed for the four visual stimuli suggest that the distribution of attention in peripersonal space is certainly not uniform along the length of hand-held tools. Interestingly, we observed the most reliable and most pronounced cross-modal attention effect for visual stimuli presented at the tip of the sticks, rather than at the hand, i.e., the location where the tactile stimuli were actually perceived.

In one experiment of Holmes et al. study (2007), the participants had to discriminate between single and double vibrotactile stimuli presented via one or two tools held in one or two hands, respectively. Participants held one tool on each side, either both uncrossed or both crossed across the midline. Single or double visual distractor stimuli presented at the tips of the tools had to be ignored. Holmes et al. (2007) reported that visual–tactile interactions were stronger on the anatomical side of space when the tools were crossed (i.e., vibrations felt at the right hand were more affected by visual distractors on the right side). It should be noted that these results are not entirely consistent with those of either Holmes et al. (2004) or the results reported here. This difference might well be related to the non-spatial nature of the participant’s task used in Holmes et al.’s (2007) study (as compared to the spatial discrimination task used in the other two studies).

It might be argued that the use of an external reference frame in the present study was forced by the instruction given to the participants, i.e., to detect tactile stimuli delivered in either the left or right hemifield. Since some authors used an attend-hemifield instruction (Eimer et al. 2001), while others used a attend-hand instruction (Röder et al. 2008), but obtained similar ERP crossing effects, we think that the remapping of tactile stimuli into an external reference frame is rather task-independent and automatic even when tools are used (though see Gallace et al. 2008). Furthermore, the lack of any ERP attention effects in response to visual stimuli in the crossed tools condition might be attributed to the more difficult (and therefore less automatic) simultaneous remapping process for tactile stimuli into a common external coordinate system. Alternatively, the need to distribute tactile spatial attention across both hemifields might have exhausted the available attention resources resulting in a lack of crossmodal attention effects. The latter post-hoc explanation could presumably be tested by systematically manipulating processing load.

It should be noted that since we used sticks which were crossed in half of the trials, the hands (i.e., the sensory epithelium that was physically stimulated) never changed hemifield. Thus, if the left vibrator was operated in the crossed stick condition, the right hand holding the stick touching the left vibrator was stimulated. This touch is projected to the left hemisphere. Thus, visual stimuli originating in the left hemifield would gain preferred processing if the hemispheric account would hold. We did, however, not observe any attention effect for visual stimuli in the crossed stick condition at all. This result argues against a hemispheric account but against the exclusive use of an external reference as well.

When externally and anatomically anchored reference systems are placed into conflict, as when tools are crossed at the midline, both early tactile and early (<200 ms) visual spatial attention effects were eliminated, while late tactile attention effects remained unchanged, thus suggesting a parallel activation of an anatomical and an external reference frame at early stages of stimulus processing but a dominance of an external frame of reference at later (>200 ms) processing stages. Thus, our data suggest, in agreement with a recent study by Holmes et al. (2004), that tool use does not simply ‘extend peripersonal space’. Instead, it appears to result in a shift of visual spatial attention toward the tip of the tool as well as to attention being focused by the hand where the touch is felt.

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References

Berti A, Frassinetti F (2000) When far becomes near: remapping of space by tool use. J Cogn Neurosci 12:415–420

Driver J, Spence C (2004) Crossmodal spatial attention: evidence from human performance. In: Spence C, Driver J (eds) Crossmodal space and crossmodal attention. Oxford University Press, Oxford, pp 179–220

Eimer M (2001) Cross-modal links in spatial attention between vision, audition, and touch: evidence from event-related brain potentials. Neuropsychologia 39:1292–1303

Eimer M, Driver J (2000) An event-related brain potential study of cross-modal links in spatial attention between vision and touch. Psychophysiology 37:697–705

Eimer M, van Velzen J (2005) Spatial tuning of tactile attention modulates visual processing within hemifields: an ERP investigation of cross-modal attention. Exp Brain Res 166:402–410

Eimer M, Cockburn D, Smedley B, Driver J (2001) Cross-modal links in endogenous spatial attention are mediated by common external locations: evidence from event-related brain potentials. Exp Brain Res 139:398–411

Farne A, Iriki A, Ladavas E (2005) Shaping multisensory action-space with tools: evidence from patients with cross-modal extinction. Neuropsychologia 43:238–248

Gallace A, Soto-Faraco S, Dalton P, Kreukniet B, Spence C (2008) Response requirements modulate tactile spatial congruency effects. Exp Brain Res (in press)

Giard MH, Peronnet F (1999) Auditory-visual integration during multimodal object recognition in humans: a behavioral and electrophysiological study. J Cogn Neurosci 11:473–490

Green D, Swets J (1966) Signal detection theory and psychophysics. Wiley, New York

Hillyard SA, Simpson GV, Woods DL, Van Voorhis S, Münte TF (1984) Event-related brain potentials and selective attention to different modalities. In: Renoso-Suarez F, Ajmone-Marsan C (eds) Cortical integration. Raven Press, New York, pp 395–414

Holmes NP, Spence C (2004) The body schema and multisensory representation(s) of peripersonal space. Cogn Process 5:94–105

Holmes NP, Spence C (2006) Beyond the body schema: visual, prosthetic, and technological contributions to bodily perception and awareness. In: Knoblich G, Thornton L, Grosjean M, Shiffrar M (eds) Human body perception from the inside out. Oxford University Press, Oxford, pp 15–64

Holmes NP, Calvert GA, Spence C (2004) Extending or projecting peripersonal space with tools? Multisensory interactions highlight only the distal and proximal ends of tools. Neurosci Lett 372:62–67

Holmes NP, Sanabria D, Calvert GA, Spence C (2007) Tool-use: capturing multisensory spatial attention or extending multisensory peripersonal space? Cortex 43:469–489

Hötting K, Rösler F, Röder B (2003) Cross-modal and intermodal attention modulate event-related brain potentials to tactile and auditory stimuli. Exp Brain Res 148:26–37

Iriki A, Tanaka M, Iwamura Y (1996) Coding of modified body schema during tool use by macaque postcentral neurones. NeuroReport 7:2325–2330

Kennett S, Eimer M, Spence C, Driver J (2001) Tactile–visual links in exogenous spatial attention under different postures: convergent evidence from psychophysics and ERPs. J Cogn Neurosci 13:462–478

Maravita A, Husain M, Clarke K, Driver J (2001) Reaching with a tool extends visual-tactile interactions into far space: evidence from cross-modal extinction. Neuropsychologia 39:580–585

Maravita A, Spence C, Kennett S, Driver J (2002) Tool-use changes multimodal spatial interactions between vision and touch in normal humans. Cognition 83:25–34

Röder B, Rösler F, Spence C (2004) Early vision impairs tactile perception in the blind. Curr Biol 14:121–124

Röder B, Föcker J, Hötting K, Spence C (2008) Spatial coordinate systems for tactile spatial attention depend on developmental vision: evidence from event-related potentials in sighted and congenitally blind adult humans. Eur J Neurosci 28:475–483

Schicke T, Röder B (2006) Spatial remapping of touch: Confusion of perceived stimulus order across hand and foot. Proc Natl Acad Sci USA 103:11808–11813

Shore DI, Spry E, Spence C (2002) Confusing the mind by crossing the hands. Cognit Brain Res 14:153–163

Spence C, Pavani F, Driver J (2000) Crossmodal links between vision and touch in covert endogenous spatial attention. J Exp Psychol Hum Percept Perform 26:1298–1319

Spence C, McDonald J, Driver J (2004) Exogenous spatial-cuing studies of human crossmodal attention and multisensory integration. In: Spence C, Driver J (eds) Crossmodal space and crossmodal attention. Oxford University Press, Oxford, pp 277–320

Yamamoto S, Kitazawa S (2001a) Reversal of subjective temporal order due to arm crossing. Nature Neurosci 4:759–765

Yamamoto S, Kitazawa S (2001b) Sensation at the tips of invisible tools. Nature Neurosci 4:979–980