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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.

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 ($1^\circ \times 1^\circ$ of£

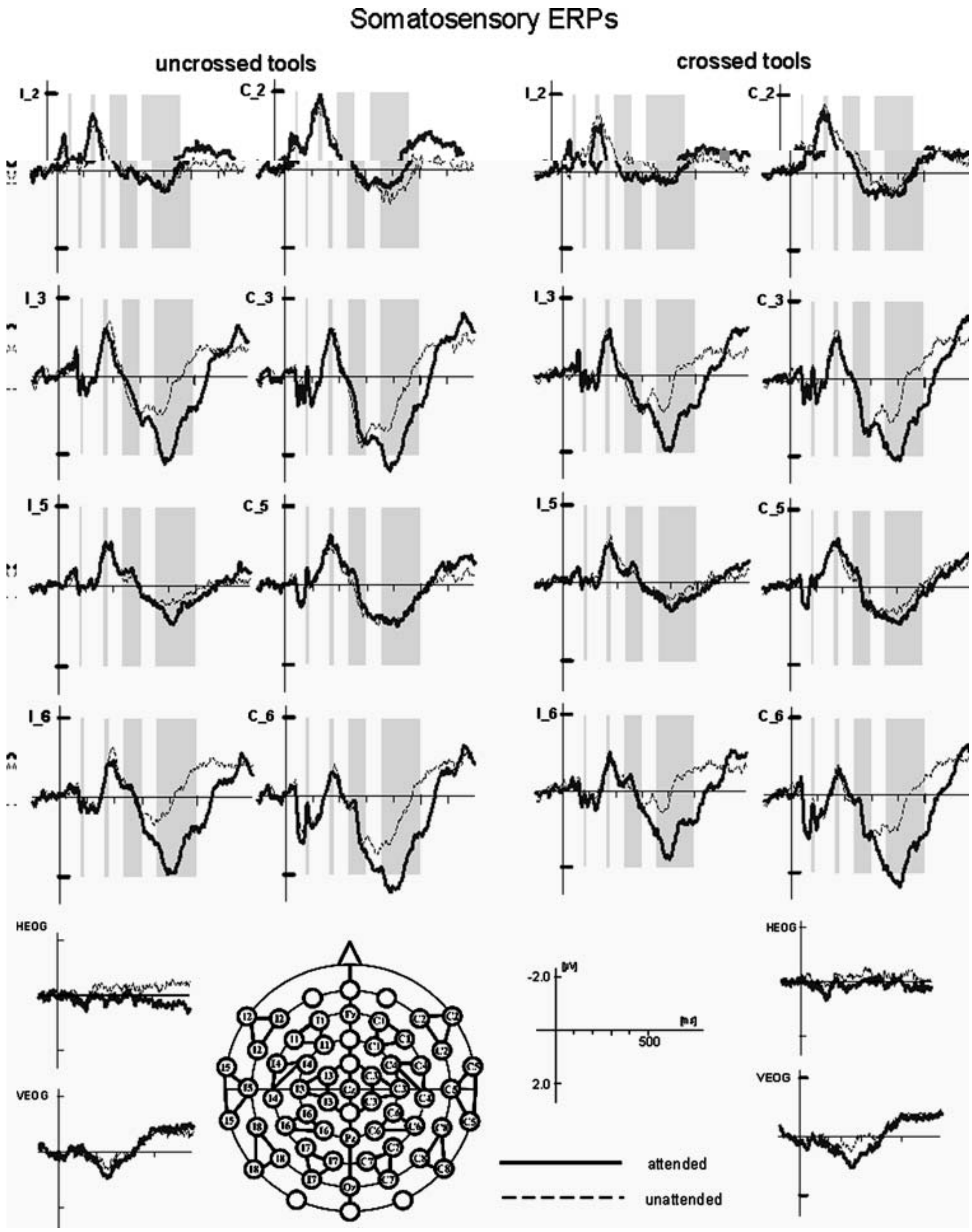

Fig. 2 Grand-averaged somatosensory ERPs elicited by tactile stimuli at the attended versus unattended location where tactile stimuli were presented (*solid* vs. *dashed lines*). All waves represent the mean signal of three electrodes (see the *lower panel*). ERPs are displayed separately for the uncrossed 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.

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 ×

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 mar-

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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 posititn of hands in space based on di fferent reference frames (Holmes and Spence 2004, 2006), including btth 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

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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 acr7(u)-6.ally(u)-6. 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

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