Brief article

Tool-use changes multimodal spatial interactions between vision and touch in normal humans

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Abstract

In a visual–tactile interference paradigm, subjects judged whether tactile vibrations arose on a finger or thumb (upper vs. lower locations), while ignoring distant visual distractor lights that also appeared in upper or lower locations. Incongruent visual distractors (e.g. a lower light combined with upper touch) disrupt such tactile judgements, particularly when appearing near the tactile stimulus (e.g. on the same side of space as the stimulated hand). Here we show that actively wielding tools can change this pattern of crossmodal interference. When such tools were held in crossed positions (connecting the left hand to the right visual field, and vice-versa), the spatial constraints on crossmodal interference reversed, so that visual distractors in the other visual field now disrupted tactile judgements most for a particular hand. This phenomenon depended on active tool-use, developing with increased experience in using the tool. We relate these results to recent physiological and neuropsychological findings. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

When we wield a long tool, we extend our possible reaching space. We can touch distant objects with the tool, so that tactile information felt at the hand can now relate to visual information from distant objects (Berti & Frassinetti, 2000; Farnè & Ladavas, 2000; Iriki, Tanaka, & Iwamura, 1996; Maravita, Husain, Clarke, & Driver, 2001). Moreover, a hand located on, say, the right side of space may contact visual objects in the left visual field with the tool, or vice-versa, given that tools can be wielded in innumerable different postures. This means that the spatial mapping between tactile stimulation at the hand,

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and any related visual information near the end of the tool, alters as a tool is used. A wielded tool may become incorporated into the 'body schema', such that the end of the tool effectively becomes an extension of the effector wielding it. Here we examined whether experience in actively wielding a long tool can modulate automatic aspects of tactile–visual spatial integration for normal human subjects. We discuss later how such a phenomenon might relate to recent physiological data on plasticity induced by tool-use (Iriki et al., 1996; Iriki, Tanaka, Obayashi, & Iwamura, 2001), and to recent neuropsychological studies on this issue (Berti & Frassinetti, 2000; Farnè & Ladavas, 2000; Maravita et al., 2001).

We exploited a visual–tactile interference paradigm previously used to study tactile–visual spatial integration in humans (Pavani, Spence, & Driver, 2000; Spence, Kingstone, Shore, & Gazzaniga, 2001). Subjects had to judge whether tactile vibrations were delivered to the thumb or index finger (equivalent to upper or lower locations here) on either hand. Visual distractor lights were fixed in vertical pairs at the far end of each of two "tools" grasped with each hand (Fig. 1). On each trial, a vibration from one of four possible locations (a finger or thumb, on the left or right hand) was presented concurrently with one of the four possible distractor lights (upper or lower, on left or right). All of the possible crossmodal pairings were equiprobable, so the visual distractors gave no information about the concurrent tactile target, and were simply to be ignored.

Previous work using visual distractors located on the hands (Pavani et al., 2000; Spence et al., 2001) showed that judgements of such tactile stimuli are slower and/or less accurate when the concurrent visual distractor is incongruent (i.e. upper vibration with lower light, or vice-versa). Importantly, this crossmodal interference has repeatedly been found to be stronger when visual and tactile stimuli appear on the same side of space (i.e. right visual field stimulation paired with vibration on the right hand, or left visual field stimulation with left hand vibration). Here we tested whether actively wielding a long tool can alter
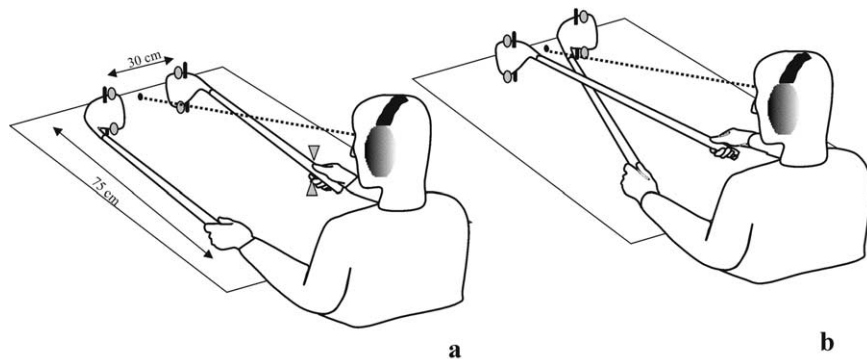

Fig. 1. Schematic of the experimental set-up: tools held in (a) straight position and (b) crossed position. In either case, a peg at the far end of the tool (shown by thick black vertical lines) was inserted into a hole to locate it, while hand locations were kept constant. Unseen tactile stimulators were placed on each tool handle at the forefinger and thumb (indicated symbolically here, for the right hand only in the straight-tool situation (a) with grey triangles). Potential visual distractors are shown as grey circles. A central LED (small black circle) had to be fixated (dotted line) during each trial. White noise through headphones masked the noise produced by vibrators.

this crossmodal mapping plastically, such that when the tools are held crossed (connecting the right hand to the left visual field, and vice-versa), crossmodal interference might now become larger from visual distractors in the opposite visual field to the tactually stimulated hand.

1.1. Experiment 1

Subjects held two long tools straight on some trials (Fig. 1a), while on other trials they crossed the far tips of the tools, while keeping the locations of the hands unchanged (Fig. 1b). Tool posture was actively changed by the observer every four trials. We hypothesized that prolonged active use of the tools in this way might alter the spatial pattern of crossmodal integration observed. Crossmodal interference should now be strongest for visual distractors currently connected to the hand by the tool. Critically, this should be observed not only in the straight posture, where distractors and hands are on the same side of space (cf. Pavani et al., 2000; Spence et al., 2001), but now also in the crossed posture where distractors are on the opposite side of external space relative to the hand.

2. Method

2.1. Participants

Twenty healthy participants (mean age 25 years) took part.

2.2. Apparatus

The 'tools' were toy golf-clubs, 75 cm long, with a vertical peg incorporated into the far end. A pair of Oticon-A bone-conduction vibrators served as tactile stimulators on the handle of each tool, one below the thumb and the other under the forefinger pad on each hand (Fig. 1a). With this arrangement, each vibrator occupied either an upper (thumb) or lower (forefinger) position on the tool handle. Two red turbo LEDs (60 cd/m^2) served as potential visual distractors, each fixed on the upper or lower margin of the far end of one tool. With this arrangement, the LEDs each rested 3 cm above or below the longitudinal axis of each tool. The vertical pegs at the far ends of the tools were each placed by the subject into a hole, to ensure the same two possible positions for the ends of the tools, regardless of whether these were uncrossed or crossed. Actively positioning the pegs required skill and dexterity, justifying our reference to the golf-clubs as "tools". Hands rested on two small rubber cubes at fixed positions. A fixation light (28 cd/m^2 green LED) was placed on the midline, between the far ends of the tools.

3. Procedure

Participants sat in a sound-proof booth with chin on a rest. On each trial, a tactile stimulus from one of the four vibrators (200 Hz sine-wave signal, in three successive 50 ms bursts, each separated by a 50 ms gap) plus a visual stimulus from one of the four distractors (same duration and frequency as the vibration) were presented. Onset of the

visual distractor occurred 30 ms before the tactile target, as pilot work showed this maximizes crossmodal interference. The positions of vibrations and visual stimuli (which could each appear on left or right, in upper or lower positions) were completely independent, being randomly selected on each trial. White noise over headphones masked the sound of the unseen vibrations. Participants judged whether each vibration was at the forefinger (lower position) or thumb (upper), regardless of the hand stimulated (left or right), while ignoring the task-irrelevant flashes. Responses were made by releasing one of two foot-pedals placed under the right foot (lifting the toes for thumb vibrations, and the heel for finger vibrations). Note that this up/down judgement, made with one foot, means that any difference in crossmodal interference from distractors on the same vs. opposite side as the tactile target (when pooling over left and right targets) cannot be due merely to stimulus-response compatibility factors (cf. Riggio, Gawryszewski, & Umiltá, 1986). Participants fixated the central fixation light throughout each experimental trial, and received feedback following inappropriate responses (either errors, or reaction times (RTs) exceeding 1500 ms) by means of a yellow LED below fixation.

The critical manipulation was that subjects actively crossed or uncrossed the far ends of the tools, between runs of four successive trials, by inserting the pegs at their ends into small holes 15 cm away from the central fixation light on either side (Fig. 1). Thus, while the hands remained in a fixed position throughout, visual distractors on one particular side could either appear in the same visual hemifield (straight condition, Fig. 1a) or the opposite hemifield (crossed condition, Fig. 1b) as the hand to which they were currently connected via the tool. Observers were prompted to change the tool positions by simultaneous activation of all four distractor LEDs. The experimenter checked that the tools were then used appropriately. A total of 480 trials were presented, divided into ten blocks, with 240 trials for straight tools and 240 for crossed tools, and with all the possible target/distractor pairings equiprobable. The entire session lasted around 60 min.

Data from the two hands were collapsed and analyzed by repeated-measure, three-way analyses of variance (ANOVAs) on the median values of RT (or error rate) in each target/distractor combination. The three factors in the ANOVA design were: Congruency between the position of vibrations and distractor lights (i.e. congruent: upper vibrations with upper lights, or lower vibrators with lower lights; incongruent: upper vibrations with lower lights or vice-versa), Relative Distractor Side (i.e. visual distractor in the same or opposite side as the unseen vibration), and Tool Position (i.e. straight vs. crossed). The critical issue was whether effects of Congruency (i.e. crossmodal interference) as a function of Relative Distractor Side would differ in relation to Tool Position; hence, the three-way interaction was of particular interest.

Because we expected that effects of tool-use might develop with experience in wielding the tools, we also examined data separately for earlier vs. later experimental blocks.

4. Results and discussion

Fig. 2a,b shows mean results for RTs and error rate in terms of the critical crossmodal interference effect, i.e. difference between incongruent minus congruent stimulus/distractor combinations, as defined above. When the tools were held straight (left pair of bars
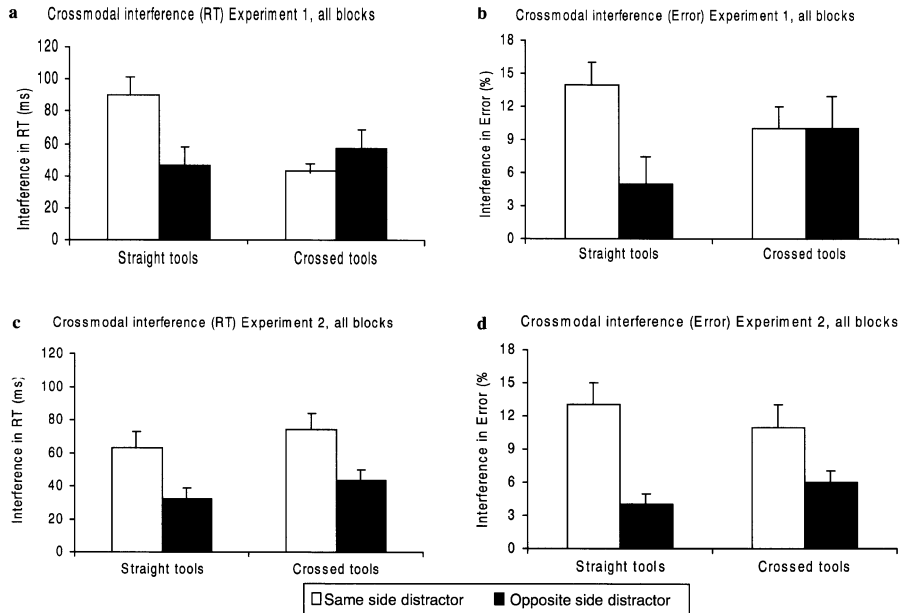
Fig. 2. Mean crossmodal interference effects in Experiment 1 (a) for RTs and (b) for errors, and in Experiment 2 (c) for RTs and (d) for errors. Interference effects were calculated as incongruent minus congruent scores (where congruency refers to crossmodal stimulus agreement in the vertical dimension only). White bars are for trials with the visual distractor in the same visual hemifield as the tactually stimulated hand, and black bars are for distractors in the opposite hemifield. Within each graph, the left pair of bars shows results with straight tools, and the right pair with crossed tools. Note that the spatial pattern of crossmodal interference (for same vs. opposite-side distractors) differed for straight vs. crossed tools in Experiment 1 but not in Experiment 2.

within Fig. 2a,b), crossmodal interference was stronger for visual distractors in the hemifield of the stimulated hand, confirming previous results (e.g. Pavani et al., 2000; Spence et al., 2001). The critical new result was that this pattern changed when the tools were crossed (right pair of bars within each graph; compare with left bars). This pattern was supported in the ANOVA analyses by the three-way interaction between Congruency, Relative Distractor Side and Tool Position, which was highly significant for RTs ($F(1, 19) = 21.2$, $P < 0.01$) and marginal but supportive of the RT pattern for error rates ($F(1, 19) = 3.6$, $P = 0.07$). Table 1 (E1) gives the means for all conditions.

Other significant terms in the ANOVAs were all qualified by the above three-way interactions (i.e. for RTs, main effects of Congruency ($F(1, 19) = 47$, $P < 0.01$) and interaction between Relative Distractor Side and Tool Position ($F(1, 19) = 17$, $P < 0.01$); for errors, main effects of Congruency ($F(1, 19) = 36$, $P < 0.01$), and Relative Distractor Side ($F(1, 19) = 4.9$, $P < 0.05$), plus interactions between Relative Distractor Side and Tool Position ($F(1, 19) = 8.5$, $P < 0.01$), and Congruency with Relative Distractor Side ($F(1, 19) = 4.7$, $P < 0.05$)).

One important question was whether the influence of tool position on the pattern of crossmodal interference depended on experience in actively using the tools, as expected

Table 1
Mean RTs (in milliseconds), percentages of errors, and mean crossmodal interference (CI), separated by condition (straight vs. crossed tools) and experiment (E1 and control experiment, E2) (standard errors in parentheses)

Experiment		Straight tools						Crossed tools					
		Same-side distractor			Opposite-side distractor			Same-side distractor			Opposite-side distractor		
		Congruent	Incongruent	Mean CI[a]	Congruent	Incongruent	Mean CI	Congruent	Incongruent	Mean CI	Congruent	Incongruent	Mean CI
E1	RT	539 (15)	629 (19)	90	546 (15)	592 (18)	46	547 (14)	590 (15)	43	557 (14)	614 (21)	57
	%	7 (1)	21 (2)	14	7 (1)	12 (2)	5	7 (1)	17 (2)	10	7 (1)	17 (2)	10
E2	RT	531 (14)	594 (17)	63	537 (14)	569 (15)	32	538 (15)	612 (17)	74	537 (16)	580 (17)	43
	%	6 (1)	19 (3)	13	7 (1)	11 (2)	4	6 (1)	17 (2)	11	5 (1)	11 (2)	6

[a] Crossmodal interference (CI) = incongruent minus congruent scores.
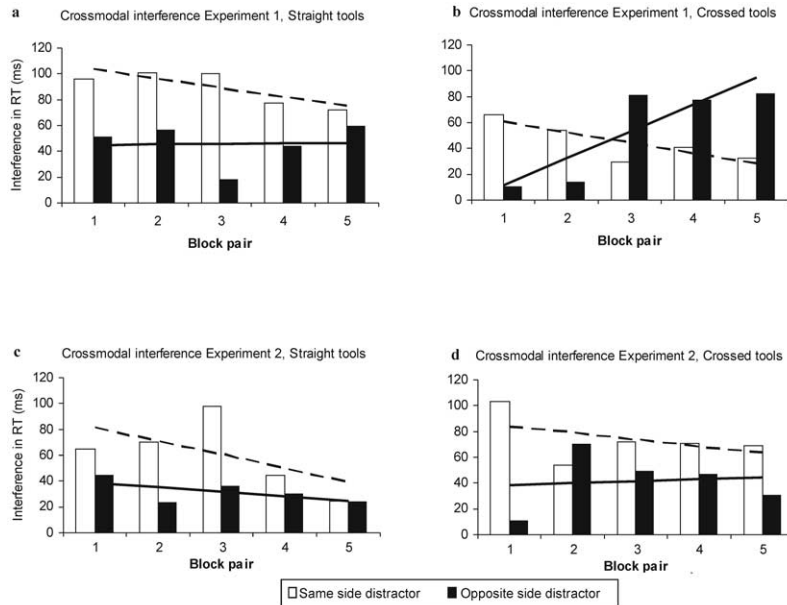
Fig. 3. Mean crossmodal interference effect for RTs as a function of successive block pairs. The upper two graphs show this for Experiment 1 (a, straight tool; b, crossed tools), while the lower two graphs show this for Experiment 2 (c, straight tools; d, crossed tools). Each bar represents a pair of blocks in order to equate the number of trials in each bar. Although each block in both experiments comprised the same number of trials, in Experiment 1 each block was divided into an equal number of trials with crossed or uncrossed tool, while in Experiment 2 each block contained only trials with one posture. Nevertheless, each block pair still represents the grand mean of 96 trials per subject (48 for same-side, 48 for opposite-side distractors) for that particular tool position across all subjects. Straight lines represent the linear correlation trend-line for same-side (dotted line) or opposite-side (continuous line) distractors. The critical result (see b) is the increase in interference for opposite-side distractors (black bars) as a function of successive block pairs, with crossed tools in Experiment 1 only.

from monkey data (Iriki et al., 1996). By comparing overall results from the first vs. second half of our experiment, we noted that the pattern of interference reversed in the second half of the experiment. To explore this statistically, we then analyzed the interference effect as a function of successive pairs of blocks (Fig. 3a,b shows this for RTs). Critically, with crossed tools, the effect of opposite-side distractors showed a positive correlation with block number ($r = 0.877$, $P < 0.05$, one-tailed) and exceeded the effect of same-side distractors by the third pair of blocks (Fig. 3b). This was not found with straight tools ($r = 0.038$, NS). A similar pattern was found for errors, where a correlation was found between the effect of opposite-side distractors and block number for crossed ($r = 0.822$, $P < 0.05$, one-tailed) but not straight tools ($r = 0.08$, NS). The change in the pattern of interference clearly occurred by the third pair of blocks. For the data from here onwards, interference became stronger for opposite- than for same-side distractors for RTs ($t(19) = 3.8$, $P < 0.01$) and errors ($t(19) = 2.4$, $P < 0.05$).

These results demonstrate that active tool-use can modulate spatial crossmodal interactions between vision and touch. Crossmodal interference from task-irrelevant visual

distractors on tactile judgements showed a spatial pattern that changed when tools were crossed. This was particularly marked in the second half of the experiment, after prolonged experience in actively wielding the tools. It was absent in the earlier phase of the study.

5. Control study: Experiment 2

To further test the importance of active tool-use for the above results, we conducted a 'passive' control study with 20 new participants (mean age 26 years), who did not actively wield the tools. Now the position (straight or crossed) for the tools only changed at the end of each block of 48 trials, rather than every four trials. Moreover, all such changes were now made by the experimenter rather than by subjects.

Results (Fig. 2c,d) revealed that crossed and straight tool positions no longer differed. Crossmodal interference was always stronger for a visual distractor in the same hemifield as the stimulated hemisphere. The critical three-way interaction between Congruency, Relative Distractor Side and Tool Position was no longer significant (RTs, $F(1, 19) = 0.01$, NS; errors, $F(1, 19) = 3$, NS). Means for all conditions are given in Table 1 (E2).

When comparing E1 and E2, no difference was found overall (RTs, $F(1, 38) = 0.416$, NS; errors, $F(1, 38) = 1.116$, NS) while the interaction between Congruency, Relative Distractor Side, Tool Position and Experiment was significant for RTs ($F(1, 38) = 8.643$, $P < 0.01$). Critically, separate ANOVAs for straight or crossed postures between experiments revealed that this different pattern between the experiments applied only for crossed tools ($F(1, 38) = 9.609$, $P < 0.01$), and not for straight tools ($F(1, 38) = 0.709$, NS).

This control study shows that the mere connection of a hand with far contralateral distractors, via a passively held tool, is insufficient to modify the spatial nature of the crossmodal interactions observed. Instead, active wielding of the tool is required, as in the first experiment. In contrast with Experiment 1, the effect of opposite-side distractors did not increase as a function of block number in the critical crossed-tools condition ($r = 0.122$, NS) (Fig. 3d).

6. General discussion

Our results show for the first time in normal adult humans that prolonged active use of tools (over several minutes) can modify visual–tactile spatial integration. The data are consistent with a progressive functional change in the 'body schema', so that with experience in actively using the tools, they became treated as extensions of the effectors wielding them. This produced a stronger integration between visual stimulation at the current location of the far end of the tool, and tactile information at the hand wielding the tool. As a result, after experience in tool-use, visual stimuli in the opposite hemifield to the stimulated hand could produce stronger crossmodal interactions than visual stimuli in the same anatomical hemifield, when the tools were crossed.

These results for crossmodal visual–tactile interactions in humans may relate to recent findings concerning visual–tactile interactions at the neurophysiological level in single cells of the monkey brain. Multimodal cells have now been found in several brain regions

that respond to both tactile and visual stimulation, with spatially congruent receptive fields in these modalities (e.g. Colby, 1998; Graziano & Gross, 1995; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981). Moreover, these receptive fields appear to be centred on the particular body part on which the tactile field lies (e.g. the hand), such that the visual and tactile receptive fields remain in correspondence even when that body part is moved separately from the eyes (Fogassi et al., 1996; Graziano & Gross, 1995).

Recent data show that when monkeys are trained to use tools to reach visual objects in far space, the visual receptive field of such multimodal cells (in the anterior bank of the intraparietal sulcus) can be enlarged, so as to now include the whole length of the tool (Iriki et al., 1996). As a consequence, bimodal neurons previously responding only to visual stimuli near the hand now start to respond also to visual stimuli at the far end of the tool. Moreover, when different mappings between hand location and the location of the end of the tool are introduced (Iriki et al., 2001), corresponding re-mappings are seen in the bimodal cells, but only after considerable practice with the new mapping. It is tempting to speculate that similar cell populations might be responsible for the crossmodal re-mapping observed here in humans, which likewise depended on experience in actively wielding the tools.

Recent neuropsychological studies of brain-damaged patients have also shown that tool-use may alter spatial representations. Berti and Frassinetti (2000) observed a right-hemi-sphere patient who showed neglect on line bisection in near but not far space, when bisecting with a laser pen, but whose neglect became apparent for far lines when these were bisected with a long tool, that brought them within (extended) reaching space. Farnè and Ladavas (2000) plus Maravita et al. (2001) observed that crossmodal visual–tactile extinction in right-hemisphere patients (whereby a right light can extinguish awareness of concurrent touch on the left hand) can also be modulated by holding a tool, such that distant lights far from the right hand (but within reach of the tool) now produce more extinction.

The present results are consistent with such tool-based modulation of visual–tactile interactions, but they differ in several respects. They demonstrate such phenomena in normal subjects for the first time, plus the dependence on experience in actively wielding the tool even for such subjects. Our results also differ in showing a reversal of the mapping of left or right visual hemifields with respect to particular stimulated hands, not just an extension into far space within a fixed hemifield, as in existing patient studies. It should be interesting to adapt the present paradigm to test whether a similar left/right reversal can be induced in neglect or extinction patients. In this way one might test whether right visual field stimulation can become the ally rather than competitor of tactile stimulation on the left hand, when a right-hemisphere extinction patient wields tools in crossed positions. If so, this could reduce the crossmodal extinction observed.

The present results show that active tool-use can alter the mapping between visual and tactile stimuli in the normal human brain, so that visual stimuli located at the current position of the tool's far end now interact most with tactile stimuli on whichever hand wields the connecting tool. This re-mapping may often be of functional use, as when visual feedback from the tool end is combined with touch to control a movement. Note, however, that the observed re-mapping could be of no strategic use to subjects in the present experiment. Here the visual stimuli could only be distracting to the unimodal tactile

task, and the tools were static during experimental trials. Our results thus suggest that the re-mapping phenomenon may not be cognitive penetrable, arising automatically even for task-irrelevant visual distractors. Our data also show that such plastic re-mapping depends on experience in actively wielding the tools. The neural basis of this phenomenon could be further studied by applying our paradigm to the multimodal tactile–visual neurons recently discovered in the primate brain (Iriki et al., 1996, 2001).

Acknowledgements

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