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RESEARCH ARTICLE

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Visual enhancement of touch in spatial body representation

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Abstract Perception of our own bodies is based on integration of visual and tactile inputs, notably by neurons in the brain's parietal lobes. Here we report a behavioural consequence of this integration process. Simply viewing the arm can speed up reactions to an invisible tactile stimulus on the arm. We observed this visual enhancement effect only when a tactile task required spatial computation within a topographic map of the body surface and the judgements made were close to the limits of performance. This effect of viewing the body surface was absent or reversed in tasks that either did not require a spatial computation or in which judgements were well above performance limits. We consider possible mechanisms by which vision may influence tactile processing.

Keywords Somatosensory cortex · Cross-modal · Somatotopic · Touch · Body representation

Introduction

Perception of our own bodies is based on integration of sensory inputs, notably by neurons in the brain's parietal lobes. Several classes of evidence suggest that the brain integrates the various sensory experiences of our own bodies. First, patients with parietal damage have specific difficulty in matching visual representations of their own body parts with their proprioceptive information. They therefore fail to recognise their own actions in a video monitor (Sirigu et al. 1999). Second, neurons have been observed in several brain areas, including the premotor cortex (Graziano et al. 1997) and parietal cortex (Obayashi et al. 2000) whose visual receptive field follows the moving arm. In the parietal cortex, correlated visual and tactile experience of the monkey's arm is required to elicit and maintain this tuning (Graziano 1999).

Psychophysical studies also show strong evidence for visual-tactile integration. First, cross-modal links in attention ensure that visual events facilitate tactile processing from the same point in space (Spence et al. 1998), and vice versa (Kennett et al. 2001a). Previous work suggests that visual enhancement of touch may involve a perceptual context effect, and is not merely attentional. Briefly, we (Kennett et al. 2001b) found significant improvements in two-point discrimination thresholds (2PDT) (Weber 1834) when participants had non-informative vision of their stimulated arm, compared to a condition which controlled for spatial attention by presenting a neutral object in the same location. This was accompanied by facilitation of the N80 component of the somatosensory evoked potential corresponding to the second wave of somatosensory cortical processing (Taylor-Clarke et al. 2002). These results are consistent with descending feedback from multi-modal areas (cf. Macaluso et al. 2000) altering the operation of a primary somatosensory cortical map.

Nevertheless, the conditions under which vision enhances touch remain unclear. Tipper and colleagues (1998, 2001) have reported acceleration of tactile simple reaction times (SRTs) when participants have concurrent vision of the stimulated body part on a video monitor. Effects were stronger for visually familiar body parts (the face) than for visually unfamiliar body parts (back of the neck). These experiments did not entirely exclude spatial attentional effects. In their experiment, imperative tactile targets could occur randomly to either hand (or in later work to any of several body locations), while only one of the hands (or body locations) was viewed on the central video monitor. In these conditions of uncertainty about tactile target location, viewing a specific body part may have caused participants to pay increased attention to the viewed body part at the expense of others. Furthermore, unlike two-point discrimination, this tactile detection task does not involve spatial computations involving a topo-

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graphic body map, nor does it involve judgements near the limits of performance.

We therefore investigated the conditions under which visual enhancement of touch occurs in a series of four experiments. These experiments aimed to establish whether the visual-tactile enhancement we observed previously was a very general phenomenon, or whether the spatial nature and high difficulty level of the 2PDT task we had previously used were necessary for visual enhancement of touch. We therefore systematically varied the spatiality and difficulty level of tactile perception tasks across four independent experiments. However, because the tasks varied considerably in their psychological demands, task difficulty could not be a strictly orthogonal factor. Thus, in experiment 1, we investigated whether visual enhancement can occur in non-spatial simple detection of tactile stimuli well above the detection threshold, as Tipper et al.'s (1998) result suggests.

Experiment 1

Materials and methods

Ten right-handed consenting healthy participants (aged 20–33 years; four males, six females) reporting normal or corrected-to-normal vision and normal touch took part in the experiment. All experiments were performed with local ethical committee approval and in accordance with the standards laid down in the 1964 Declaration of Helsinki.

A miniature solenoid tapper was attached to the left dorsal forearm, 50 mm proximal to the ulnar styloid process. The left arm was positioned in a box beneath a semi-silvered mirror (see Fig. 1). When the box interior was illuminated participants saw their arm (*view arm* condition) and the attached tapper. When the lights were off participants saw a neutral object (*view object* condition). This was a strip of white paper, suspended above the mirror, having the approximate dimensions and the same distance from the eye of the viewed forearm. A marker on the paper corresponded to the tapper location.

Prior to the experiment, participants aligned the tapper and their arm with the images of the marker and the neutral object. Participants foveated the tapper, or the corresponding marker, throughout and the experimenter verified this. The tapper was activated for 100 ms after a variable foreperiod (1,500–2,500 ms), creating a suprathreshold tactile stimulus. Participants made simple speeded responses to taps with their right hand on a computer key. A video control condition based on that reported previously (Kennett et al. 2001b) confirmed that solenoid activation was invisible and inaudible. Vision was therefore non-informative for tactile processing. Each condition comprised two blocks of 40 trials each. The conditions were arranged in ABBA order, counterbalanced across participants.

Results

Two trials (<0.1%) were rejected, as RTs were over 1,500 ms. No formal error analysis was performed, as errors are rare and hard to interpret in supra-threshold simple detection tasks. The median RTs were calculated in each condition. The mean of participants' median RTs was 250 ms (SD=55 ms) in the view arm condition, and 247 ms (SD=47 ms) in the view object condition. These values did not differ significantly ($t(9)=0.3$, $p=0.8$).

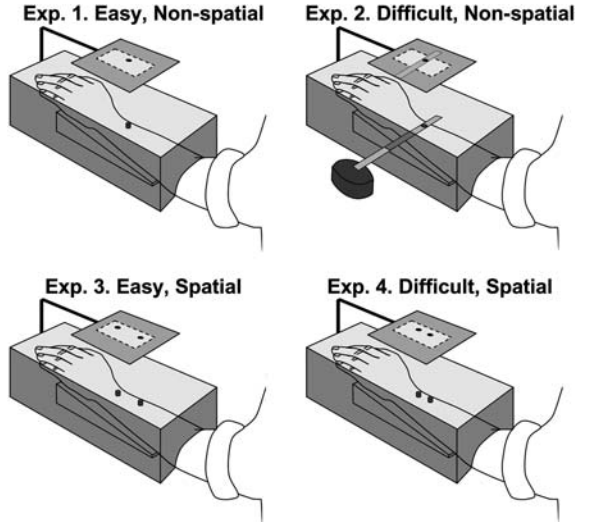

Fig. 1 Schematic view of the set-up in the four experiments. Participants placed their left arm inside a box on a foam bolster to position the tactile stimuli at a fixed location. The top side of the box was a semi-silvered mirror (pale shading) through which the arm could be seen when the box interior was illuminated (view arm). When the box was dark, the mirror appeared opaque but reflected a white rectangle (*dashed line*) on a black background mounted above (view object). The rectangle had a marker/markers placed on it that appeared in the same position(s) as the tactile device(s) would when visible. Positioning of the arm and object was performed carefully such that the subject saw the rectangle and markers inside the box where the arm was placed. In experiment 2, the stimulus was vibrated via a flat transparent rod which entered the box from the side. An equivalent flat rod was attached to the object to maintain similar views across view conditions. In experiment 3 the separation between the two tappers was 45 mm. In experiment 4, the separation was set separately for each subject based on an estimate of their tactile acuity. The mean separation was 23 mm

Discussion

We found no visual enhancement of tactile sensation in a speeded suprathreshold simple detection RT task. This null result does not reflect low statistical power, since overall performance was slower in the view arm condition in which visual enhancement might be expected. Moreover, five participants performed faster in the view object condition and five performed faster in the view arm condition. One possible, though unlikely, explanation of the lack of enhancement is that participants saw the neutral object as a proxy for their arm, attributing it to themselves. In this case, both conditions could show equal visual enhancement of touch. This possibility is addressed in experiment 4.

Our result contrasts with a significant 14 ms visual acceleration of tactile detection reported previously (Tipper et al. 1998). One important difference between that experiment and ours was the certainty with which target stimuli were presented on one hand. In their experiment, participants were unsure on which hand the target would appear. Another crucial difference was our use of a neutral object to control for spatial attention. In contrast, their equivalent control condition was a view of the opposite, currently unstimulated, hand located in a different spatial location. Therefore, viewing one hand rather than the other could produce a tactile attentional advantage for the viewed hand, thus speeding performance. In our experiment the spatial location of the two views, and of the target location, was held constant, thus removing shifts in spatial attention between possible target locations or viewed locations.

Second, our results contrast with the significant visual enhancement of touch found previously using the 2PDT task (Kennett et al. 2001b; Taylor-Clarke et al. 2002). 2PDT requires participants to enumerate stimuli based on their location on the body, and thus involves use of somatosensory maps. Furthermore, the 2PDT task involves difficult spatial discriminations close to the limits of performance. The present experiment used similar tactile stimuli and visual conditions, but required only simple detection, without any spatial computation. All the individual stimuli were clearly detectable.

Experiment 2

Experiment 2 investigated whether increasing the task difficulty in a speeded non-spatial task would reveal visual-tactile enhancement. The experiment looked for the enhancement effect on non-spatial discrimination between tactile stimuli close to the limits of discrimination performance. Nineteen new consenting adults (aged 19–55 years, six males, thirteen females) participated.

A small circular disc (diameter 7 mm) rested on the left dorsal forearm approximately 50 mm proximal to the ulnar styloid process (i.e. in the same location as the stimulus in experiment 1). The upper surface of the circular disc was attached to a flat transparent perspex bar that crossed the width of the forearm but did not touch the skin (see Fig. 1). This plastic bar was attached to an object, out of view, that vibrated under computer control. The vibration was transmitted along the plastic bar to the circular disc so that a buzz was felt at the location of the disc. The view arm condition was as in experiment 1. The neutral object condition was also identical to experiment 1 except that the visual marker now also included a duplicate transparent plastic bar.

The experimenter positioned the participant's arm to align the disc and bar locations with the reflections of the neutral object bar and marker. A buzz was delivered to the forearm at a frequency of 100 Hz at an amplitude well above the absolute threshold level for detection, though weak compared to the tactile stimuli used in the other experiments. The buzz could either be continuous (no gap trials) or contain a short temporal gap without vibration (gap trials). A beep signified the beginning of a trial and white noise was delivered through headphones for 2,000 ms following the beep to mask any auditory cues. The beep was applied in this experiment to alert participants to the upcoming vibrations in the current trial. The buzz, lasting 250 ms, occurred after a random foreperiod of 500–1,000 ms. For gap trials, the delay occurred 75 ms after buzz onset.

The limits of performance for temporal gap detection for each participant were determined from a previously run unspeeded staircase procedure. Participants performed separate staircases viewing their arm and the object, as in the main experiment, while sitting in a darkened room. Briefly, a large initial gap in the stimulus was progressively reduced until participants made an error in their unspeeded judgement of the presence of the gap (1st reversal). The gap duration was then increased, with half the step size, until the participant answered correctly (2nd reversal), then reduced again, again halving step size. The 5th reversal was taken as the gap detection threshold. The mean value for all conditions provided the gap duration for the gap trials. Participants then performed a short practice speeded discrimination block of 20 trials (20% no gap trials) with no vision. Participants discriminated between gap and no gap trials with a speeded choice response, using two computer keys with their right hand. If accuracy in this practice block was below 65% or above 85%, the gap duration was adjusted to bring performance within this range if possible. Gap durations used in the detection RT task varied between participants from 26–110 ms (mean 61 ms). Once a suitable gap duration was found, participants performed 100 trials in each condition (20% no gap), in separate blocks counterbalanced across participants.

Results

Six participants who scored less than 60% correct in one or both visual conditions were excluded from the analysis. Eighty trials (3.1%) were removed due to technical error. The median RTs were calculated in each condition. The mean of participants' median RTs was 661 ms (SD=277 ms) in the view arm condition, and 659 ms (SD=244 ms) in the view object condition. These values did not differ significantly ($t(12)=0.05$, $p=0.96$). Mean percentage correct was calculated in each condition. Mean accuracy was 72.4% (SD 8.5) in the view arm condition and 76.5% (SD 7.2) in the view object condition. Performance in the view arm condition was significantly less accurate than performance in the view object condition ($t(12)=2.5$, $p=0.03$).

Discussion

We found no visual enhancement of performance in this difficult and non-spatial RT task. Merely pushing tactile processing close to the limits of performance is not sufficient to produce visual enhancement of touch. Indeed, in this task participants' accuracy was significantly higher when viewing the object compared to viewing the arm. This result is unlikely to reflect a speed-accuracy trade-off as the higher accuracy in the view-object condition was not accompanied by slower performance. A possible explanation for greater accuracy in view-object will be discussed later.

This result again contrasts previous observations of visual enhancement, both in Tipper et al.'s (1998) simple detection task and in our 2PDT task. Clearly, viewing the body while tactile stimulation is close to the limit of tactile performance is not sufficient to produce visual enhancement of touch. Spatial computation using a somatotopic map may also be required.

Experiment 3

Experiment 3 investigated the effect of viewing condition on tactile performance in an easy and spatial RT task. Eight new participants (ages 18–34 years; four males, four females) were tested.

The methods broadly resembled experiment 1. However, two tappers were now used, centred on the location stimulated previously. The tappers were positioned 45 mm apart, arranged along the forearm, well above the 2PDT distance (Kennett et al. 2001b) so that the location could be easily discriminated and the experimenter verified that this was the case. The visual conditions were identical to experiment 1 except that the neutral object now included two visual markers corresponding to the two tactile stimulators. Participants foveated between the two tappers, or the corresponding markers, and the experimenter visually monitored that this eye position was maintained throughout. Taps were delivered by either tapper with equal random probability. Participants discriminated the activated tapper with a speeded choice response, using two computer keys with their right hand. These response keys were arranged parallel to the stimulated arm, with the far response key corresponding to taps from the far tapper. Each participant performed 80 trials in each condition. Conditions were tested in separate blocks, counterbalanced across participants.

Results

Seven trials (<0.1%) were removed, as RTs were over 1,500 ms. The median RTs were calculated in each condition. The mean of participants' median RTs was 501 ms (SD 53 ms) in the view arm condition, and 478 ms (SD 51 ms) in the view object condition. These values differed significantly ($t(7)=3.0$, $p=0.02$). Performance accuracy across participants was 91.9% (SD=6.0) in the view arm condition and 92.6% (SD=3.2) in the view object condition. These values did not differ significantly ($t(7)=0.7$ $p=0.7$)

Discussion

We found no visual enhancement of tactile performance in this speeded, relatively easy spatial discrimination task, again contrasting with our previous observations of visual enhancement in a 2PDT task. In fact, participants were significantly faster in view object compared to view arm conditions. This result is unlikely to reflect a speed-accuracy trade-off as the tendency was for more accurate responses in the view object condition. A possible explanation for faster performance in the view object condition will be discussed later.

The absence of visual enhancement suggests that spatial computation involving the somatotopic map of the body surface is not sufficient for visual enhancement to occur. Both spatial computation and judgements close to the limit of tactile performance may be required. Therefore, in experiment 4 we used a spatial task close to the limits of tactile performance to investigate whether visual enhancement of touch could be observed in a reaction time task when both spatial computation *and* judgements close to the limit of performance are required.

Experiment 4

Eighteen new right-handed healthy consenting participants (ages 18–39 years; nine males, nine females) took part.

The methods broadly resembled experiment 3. Two tappers were used, arranged along the forearm and centred on the location stimulated previously, but now they were placed at a separation close to the 2PDT distance. The 2PDT for each participant was determined using a simple staircase procedure, as for experiment 2. Briefly, a large initial separation between two plastic rods was progressively reduced until participants made an error in judging the number of stimuli (1st reversal). The separation was then increased, with half the step size, until the participant answered correctly (2nd reversal), then reduced again, again halving step size. The 5th reversal was taken as the 2PDT. The solenoid tappers for the discrimination experiment were then positioned at 80% of this 2PDT estimate. This value was chosen following pilot studies to ensure the discrimination task was performed with approximately 75% accuracy. Spatial discrimination between single stimuli is generally more accurate than enumeration of two separate simultaneous stimuli in 2PDT tasks (Weber 1843), therefore allowing our participants to perform above chance despite being close to the two-point threshold. Separations varied between participants from 15–35 mm (mean 23 mm) and so was always well below the 45 mm separation used in the easier version of this task (Expt. 3).

Taps were delivered by either tapper with equal random probability. Participants discriminated the activated tapper (near or far) with a speeded choice response, using two computer keys with their right hand as for the previous experiment.

The view arm condition was as for the previous experiments. The *rectangular object* condition was identical to the neutral object condition of experiment 3. An additional condition controlled for possible visual enhancement if participants attributed the supposedly neutral object to themselves. In this *circular object* condition, participants viewed a black paper circle (diameter 85 mm) with white markers in the tapper locations. This was designed to have very different spatial features from an arm and thus not support attribution. The experimenter moved the participant's arm to align tapper locations with the reflections of the neutral object markers. Participants foveated between the two tappers, or the corresponding markers. Each participant performed 80 trials in each condition. The conditions were tested in separate blocks, counterbalanced across participants.

A control experiment ensured that vision of the arm was not informative. Two participants viewed 40 taps on the experimenter's arm. Participants judged which tapper (near or far) was activated on each trial. They performed at chance (58%, p=0.2 and 55%, p=0.3), confirming that the sight and sound of the taps carried no information supporting tactile discrimination.

Results

Twenty-three trials (0.5%) were removed, as RTs were over 1,500 ms. Median RTs for correct trials were calculated as before. The mean of participants' median RTs and error rates is shown in Table 1.

An ANOVA showed an overall effect of condition on RT ($F_{(2,34)}$=7.0, p=0.003). Planned comparisons showed that RTs were faster for view arm than for rectangular object (t(17)=2.8, p=0.01) or circular object (t(17)=4.0, p<0.001). There was no significant difference between these two object conditions (t(17)=0.5, p=0.6).

An ANOVA on performance accuracy showed no significant effect of condition ($F_{(2,34)}$=2.0, p=0.2). However, accuracy was numerically lowest in the view arm condition (see Table 1 and Fig. 2). We used two statistical techniques to investigate whether the observed visual enhancement of RT arose merely from a speed-accuracy trade-off. First, we replicated the ANOVA analysis with a MANOVA, to discriminate between conditions using both RTs and error rate variables simultaneously. The effect of condition was unsurprisingly significant (Wilks' Lambda=0.58, equivalent to $F_{(4,66)}$=5.2, p=0.001). The MANOVA Standardised Canonical Coefficients show the contribution of the two variables, RT or error rate, to discriminating between the conditions (RT: 2.8; Error rate: −1.4). Assuming a linear speed-accuracy trade-off (Luce 1986) and with equally sensitive measures of speed and accuracy, these coefficients would be equal. The effect of condition on RT is therefore twice as salient as the effect on error rates.

Secondly, analysis of covariance (ANCOVA) was used to adjust the RT data for any speed-accuracy trade-offs. This model effectively compares median RTs after adjusting values assuming a linear relation between RT and errors. This assumption is reasonable for the range of accuracies found in this experiment (Luce 1986). The error rate itself was a poor predictor of RT ($F_{(1,52)}$=0.1, p=0.7). However, the effect of condition was even more significant after this adjustment ($F_{(2,33)}$=9.1, p<0.001; see

Table 1 Mean of median correct reaction times and error rates for experiment 4

	RTs/ms			Errors/%		
	Circle	Rectangle	Arm	Circle	Rectangle	Arm
Mean of medians	549	555	514	22.7	22.2	25.4
Standard deviation	108	104	93	10.6	10.3	10.7
Adjusted mean	549	556	512	-	-	-
Standard deviation	107	103	93	-	-	-

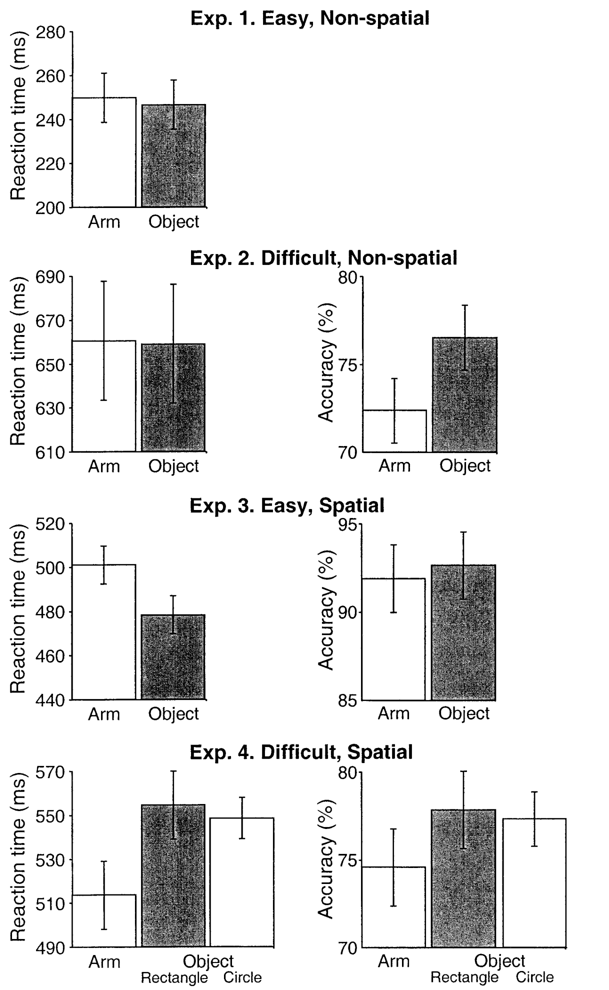

Fig. 2 Graphs showing mean of median RTs and performance accuracy across the viewing conditions in each of the four experiments. The omission of an accuracy graph for experiment 1 is to prevent misleading comparisons between this simple detection experiment and the other speeded discrimination experiments. Error bars show within-participants statistical significance bars as advocated by Christian D. Schunn (www.hfac.gmu.edu/SSB/) for important pairwise comparisons (non-overlapping error bars denote reliable differences)

Table 1 for adjusted RTs). Planned comparisons again confirmed that RTs were faster for view arm than for either object condition (both $t(17)>3.0$, $p<0.007$) and that the two object conditions were not significantly different ($t(17)=0.6$).

Discussion

Experiment 4 found reduced RTs in a difficult speeded tactile location discrimination task when participants viewed their arm, compared to two control conditions in which they viewed neutral objects. This study demonstrates facilitation in a speeded location discrimination judgement, generalising the effect found with an unspeeded numerosity judgement (Kennett et al. 2001b). This visual enhancement was not a trivial consequence of viewing the tactile event itself. Statistical analyses indicated it was not simply due to less accurate performance when participants viewed their arm. This result is consistent with our previous report of decreased unspeeded 2PDTs when viewing the arm (Kennett et al. 2001b). We have not attempted to replicate the previous performance advantage that viewing the arm conferred over viewing darkness (Kennett et al. 2001b) since gaze and/or spatial attention may wander in darkness, thus modulating tactile performance independently of the content of the view itself.

General discussion

Comparison of experiments 1–4

Comparison of our four experiments sheds light on the generality of visual enhancement of touch. These findings are summarised in Table 2.

Visual enhancement of touch was found in the difficult spatial location discrimination task only (Expt. 4). This visual-tactile enhancement was not due to spatial attention, since the viewed object appeared at the same location in space, whether it was the subject's arm or a neutral object. Comparing across four reaction time experiments, both the spatial condition and the difficulty condition had to be satisfied for enhancement to occur. A spatial task in which spatial discrimination was easy (Expt. 3), and a difficult non-spatial discrimination task (Expt. 2) did not show enhanced tactile performance when viewing the body surface compared to the neutral object. The apparent specificity of the conditions required for vision of the arm to enhance tactile performance illustrates the special nature of this visual enhancement effect. We emphasise that the four tasks studied here do not differ by strict factorial manipulation of spatiality or of difficulty. Indeed, it is not clear how difficulty could be varied as a fixed effect across tasks which involve psychologically quite different processes. While performance accuracy shows us that experiment 2 was demonstrably more difficult than experiment 1, and experiment 4 was more difficult than experiment 3, the way in which difficulty was varied was not identical in the two cases. Nevertheless, we showed that difficulty, in an operational sense, does modulate the visual-tactile enhancement effect for a speeded location discrimination task.

Interestingly, we found that vision of the arm was a *disadvantage* compared to vision of a neutral object in our tasks requiring either an easy spatial computation (Expt. 3) or difficult non-spatial discrimination (Expt. 2). This is the inverse of the visual-tactile enhancement effect found in experiment 4, and previously (Kennett et al. 2001b). We believe this is the first time advantages for viewing a neutral object, rather than the body, have been reported. This visual-tactile impairment was not predicted, and was not the primary focus of our study; however, we will consider and reject one possible explanation. General cognitive resources might be divided between touch and vision in the experiments reported here. Moreover, the views of arm and body might absorb different amounts of resource, for example if one view is more interesting than the other. If viewing the neutral object absorbed fewer resources than viewing the arm, then more resources would be available for the tactile task. This could produce better tactile performance in the view object condition. However, the result from experiment 1 renders this account implausible. Simple speeded detection is known to be sensitive to such divisions of resources across modalities (e.g. Post and Chapman 1991; Spence and Driver 1997). The absence of any effect of view in our experiment 1 suggests that our view manipulation did not also manipulate the division of resources across touch and vision. Therefore, we have no specific explanation of the improvement in tactile performance when viewing a neutral object compared to viewing the body in experiments 2 and 3. Future research could investigate the conditions under which visual-tactile *impairment* occurs.

We now investigate a possible explanation of the visual enhancement effect on modulation of receptive field size in somatosensory cortex.

Table 2 Summary of experiments

Experiment	Task	Spatiality	Difficulty	Result	Effect of non-informative vision on touch
1.	Simple reactions to taps	Non-spatial	Easy	View arm = view object	None
2.	Vibrotactile gap detection	Non-spatial	Difficult	View object >view arm	Disadvantage
3.	Location discrimination of taps	Spatial	Easy	View object >view arm	Disadvantage
4.	Location discrimination of taps	Spatial	Difficult	View arm >view object	Enhancement

Modulation of receptive fields

This account of visual enhancement invokes the topographic body map in the somatosensory cortex. The somatosensory cortex is thought to underlie perception of tactile spatial localisation (Weber 1834; Penfield and Rasmussen 1950). For example, visual enhancement would occur if descending corticocortical connections from multimodal areas such as posterior parietal cortex could tune the somatosensory map to decrease effective receptive field size. Such changes in tactile receptive field size would clearly be most advantageous for performance in difficult, spatial tasks. Although receptive field size change per se would be unlikely to influence non-spatial task performance, there may be other benefits that would facilitate performance. For example, greater cortical representation of the body part might reduce noise in brain output, as more neurons would fire in response to stimulation (McLeod et al. 1998).

Several studies show that the somatosensory cortex exhibits remarkable plasticity: the cortical territory of a body part may be increased by training (Recanzone et al. 1992; Hamilton and Pascual-Leone 1998). These changes are more pronounced in discrimination tasks than in passive stimulation (Braun et al. 2000), suggesting that such task-related plasticity is driven by spatial processing within topographic body maps.

Whether plasticity of somatosensory maps can occur fast enough to explain our findings is unclear. Studies of human tactile perceptual training report changes over periods of days or longer (Borsook et al. 1998), too slow to underlie the effects reported here. However, amputation (Merzenich et al. 1984) and denervation studies in animals (Calford and Tweedale 1991) reveal rapid (1 min) reassignment of cortical units previously representing the amputated/denervated digit to adjacent intact body parts. Removal of normal input to a cortical unit by amputation may unmask latent connections from "rival" adjacent body parts competing to own the cortical cell (Recanzone et al. 1992). We hypothesise that visual enhancement could alter tactile performance by modulating this normal process of mutual inhibition between receptive fields.

Work on primate tool use (Iriki et al. 1996) suggests that several independent visuotactile representations might be stored concurrently. Monkeys who learn to use a tool after a 2-week training period, show expanding visual receptive fields of bimodal parietal neurons along the length of the tool, or towards its representation in a video monitor (Iriki et al. 2001). The expansion reverses when the tool is put down, and rapidly re-expands when the tool is picked up, indicating a switching process between visuotactile representations. Those studies have focussed on changes in *visual* receptive fields. We speculate that *tactile* body representation may also involve switching in somatosensory cortex to select an appropriate map from possible alternatives.

Conclusion

Four experiments studied the enhancement of touch by non-informative vision of the touched body part. Visual enhancement was only found when the tactile task was *both* difficult, close to the limit of tactile performance, and *also* spatial, involving a somatotopic map of the body surface. We failed to find visual enhancement of a non-spatial speeded tactile simple detection task. We found no visual enhancement of simple tactile detection when controlling for spatial attention (Expt. 1). Interestingly, we found a disadvantage of viewing the arm in difficult non-spatial discrimination (Expt. 2) and in easy spatial discrimination (Expt. 3). Visual enhancement of touch appears to rely on a quite specialised multimodal interaction. Existing models of cross-modal integration, based on sensor fusion, do not apply to our effects, since vision is demonstrably non-informative. Instead, we propose that visual information changes the spatial representations of the body surface that the brain computes. One possible method would be adjusting effective receptive field sizes in the somatosensory cortex.

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