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Dynamic and predictive links between touch and vision

Abstract We investigated crossmodal links between vision and touch for moving objects. In experiment 1, observers discriminated visual targets presented randomly at one of five locations on their forearm. Tactile pulses simulating motion along the forearm preceded visual targets. At short tactile-visual ISIs, discriminations were more rapid when the final tactile pulse and visual target were at the same location. At longer ISIs, discriminations were more rapid when the visual target was offset in the motion direction and were slower for offsets opposite to the motion direction. In experiment 2, speeded tactile discriminations at one of three random locations on the forearm were preceded by a visually simulated approaching object. Discriminations were more rapid when the object approached the location of the tactile stimulation and discrimination performance was dependent on the approaching object's time to contact. These results demonstrate dynamic links in the spatial mapping between vision and touch.

Keywords Dynamic links · Predictive links · Touch · Vision

Introduction

An insect running down a boy's arm poses a challenging problem for the human brain. In order to determine

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whether the felt movement is due to a mosquito that should be squashed or a beetle that should be collected, the boy needs to quickly and accurately direct his visual attention towards the insect. This crossmodal shift of attention towards a moving object is considerably more complex than towards a static stimulus like a tap on the shoulder. Not only must the boy's brain integrate the tactile and visual maps of external space, it must do so in a dynamic, predictive manner. To accurately direct visual attention towards location where the insect *will be*, the predicted future location of the insect generated from the sense of touch must be used to update the visual map of external space.

Previous research on crossmodal shifts of attention has primarily examined orienting to spatially static stimuli. In a series of studies, Driver, Spence, and colleagues (reviewed in Driver and Spence 1998a) have demonstrated strong crossmodal links in spatial attention for visual and tactile stimuli. Using an orthogonal cueing method (described below) that removes response priming artifacts, it has been found that visual judgments are roughly 30 ms faster when preceded by a tactile cue (a vibration on the finger) in the same spatial location, and that tactile judgments are roughly 20 ms faster when preceded by a visual cue (a sudden flash of light). These findings suggest that spatially coincident, static events from difference sensory modalities are integrated into a unitary multimodal percept (Driver and Spence 1998a).

Even for static stimuli like vibrations and flashes, the brain is faced with the challenging problem of coordinating the maps of space for the different senses. Each time you move your hands or your eyes the retinal location that corresponds to a given position on your skin changes, so that the links between the senses must be updated. In an elegant variation of their cueing paradigm, Driver and Spence (1998b) examined this remapping in the orienting of spatial attention. When the participant's hands were uncrossed, a vibration on the left finger resulted in faster visual judgment on the left side of the visual field. Conversely, when their hands were crossed, a vibration on the left finger resulted in faster visual judgment on the right

side of the visual field. The linking between areas on the body and retina reversed to maintain an appropriate mapping in external space. However, in this study, data for crossed and uncrossed conditions were collected in separate runs so that reorienting was discrete. In the real world, this must be done continuously and dynamically.

These psychophysical findings on static crossmodal links are consistent with physiological studies of multimodal neurons in the cat superior colliculus. In a series of studies, Stein and Meredith (1993) have found neurons that have a stronger cellular response when the animal is presented with information from two sensory modalities as compared with unimodal stimulation. This response enhancement only occurs when the stimuli from the two modalities are presented at roughly the same location in external space and when they occur roughly simultaneously. Recently, multimodal cells with similar response characteristics have been found in cortical neurons (Wilkinson et al. 1996; Andersen et al. 1997).

Are there crossmodal links between vision and touch for dynamic, moving stimuli? What are the temporal and spatial factors that influence sensory integration for the dynamic multimodal stimuli we encounter in the everyday world? These are the questions we sought to address in the present study. In experiment 1, we examined whether the visual map of external space can utilize motion information from the sense of touch. We used a simulation of the crawling insect example described above: following simulated tactile motion along their forearm, participants discriminated the location of visual targets presented above their arm. In experiment 2, we examined whether predictive visual information can be used to reorient tactile attention. Following Spence and Driver, we used an orthogonal cueing paradigm such that the simulated motion was spatially uninformative for the participant's task.
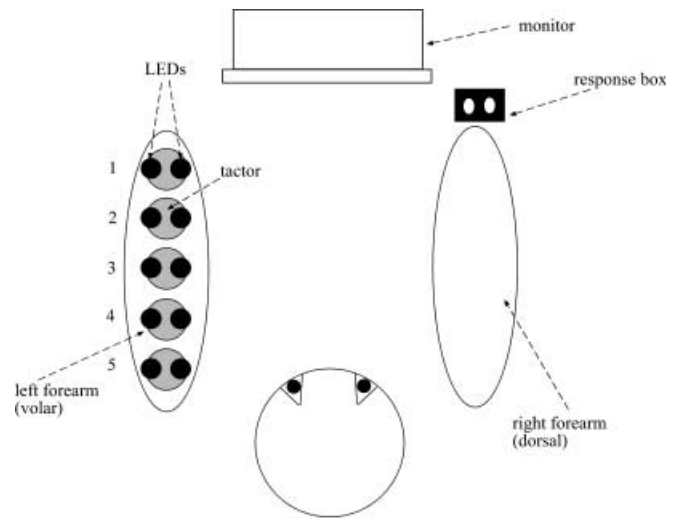
Experiment 1

Materials and methods

Six participants (three men and three women; all right handed) had a mean age of 24 years. All participants were naïve to the aims of the experiment. After explanation of the experimental procedures, participants gave informed written consent. The work was approved by the ethics committee at Nissan Cambridge Basic Research.

Apparatus and materials

The experiment was conducted in a darkened room with the participant seated at a table and directly facing a computer monitor (ViewSonic model PT795) at a distance of 57 cm. A small red cross presented at the center of the monitor was used as a fixation point and head movements were precluded with a headrest. Throughout each experimental run, white noise was played continuously through headphones so that participants could not hear the tactors. Participants were instructed prior to the experiment to maintain fixation on the cross, which was presented throughout the duration of each trial.

A schematic view of the experimental apparatus is shown in Fig. 1. Tactile stimulation was produced by five vibrotactile stimulators (diameter 4 cm) strapped to the participant's forearm and wrist. Tactors were mounted on the left arm for all participants. Each tactor could be driven by a variable duration sinusoidal pulse.

Fig. 1 Experiment 1 apparatus. Participants fixated a cross on a computer monitor for the duration of each trial. Tactile stimulation was produced by five vibrotactile stimulators (*gray circles*) strapped to the participant's left forearm and wrist (numbered *1–5*). Tactors were turned on in sequence to simulate motion up or down the observer's forearm. The participant's forearm was oriented perpendicular to the monitor. Visual targets consisted of pairs of red LEDs (*small black circles*) mounted on foam attached to the top of each of the vibrators. On each trial only one LED was illuminated and the participant's task was to determine whether the illuminated LED was from the left column (further from their midline) or the right column (closer to the midline). They indicated their choice by pressing one of two microswitches on the response box placed below their right hand. White noise was played continuously through headphones so that participants could not hear the tactors

Tactors were turned on in sequence (as described below) to simulate motion up or down the observer's forearm. The frequency of the pulse was between 290 and 306 Hz (corresponding to the resonant frequencies of the five tactors). Tactors were spaced 5.5 cm apart from center to center. Participants sat with their left palm facing up and their right palm facing down with their arms shoulder-width apart resting on the table. Visual targets consisted of pairs of red LEDs mounted on foam and attached to each of the tactors. Each pair of LEDs was 5 cm apart and mounted perpendicular to the participant's forearm as shown in Fig. 1.

Procedure

At the start of each trial a series of vibrations was used to simulate motion along the forearm. Single 75-ms pulses were sequentially applied to each tactor. The duration between each pulse was 90 ms. The direction of motion could be either towards the wrist or towards the shoulder and was chosen randomly from trial to trial. The number of tactors used to simulate the motion was chosen randomly from trial to trial. Referring to the numbers in Fig. 1, the possible motion stimuli for motion towards the shoulder were {(1, 2, 3); (1, 2, 3, 4); (1, 2, 3, 4, 5, 1, 2); (1, 2, 3, 4, 5, 1, 2, 3); (1, 2, 3, 4, 5, 1, 2, 3, 4)}, where the numbers each correspond to the particular tactor that was pulsed. These sequences were chosen so that the vibration did not end at either vibrator no. 1 or no. 5. A variable duration after the last vibration in the tactile sequence, one of the ten LEDs was turned on for 90 ms. The participant's task was to determine whether the LED was from the left column (further from their midline) or the right column (closer to the midline). They indicated their choice by pressing one of two microswitches placed below their right hand. The trial terminated if no response had been made within 1,000 ms of LED onset. The ISI

between the offset of the last vibration in the sequence and the onset of the LED was chosen randomly from one of three values (75 ms, 150 ms and 225 ms). There was a 500-ms interval between trials. The spatial relationship between the position of the LED that was illuminated and the position of the last vibration in the sequence was varied from trial to trial. The three possible relationships were (1) the last vibration in the sequence and the visual target were in the same spatial location (Same) relative to the participant's wrist, (2) the visual target was one position closer to the participant's *wrist* than the last vibration (Close-W), (3) the visual target was one position closer to the participant's *shoulder* than the last vibration (Close-S). There were 108 trials per run (3 ISI values × 3 spatial positions × 2 directions of tactile motion × 6 repeats) and each participant completed 15 runs.

It should be emphasized that in this task the tactile motion direction and left-right judgment for the visual task are orthogonal so that the position of the last vibration in the sequence was uninformative for the participant's task. Participants were told that on some trials the last tactile stimulation would occur in the same location as the LED that was illuminated and on some trials they would be in different locations.

Results and discussion

The main variable of interest in experiment 1 was the spatial relationship between the last vibrator in the sequence and the visual target. Figure 2 shows mean reaction times (RTs) for the visual judgment averaged over the six participants as a function of ISI. Data in Fig. 2A are for tactile motion towards the participant's shoulder and data in Fig. 2B are for motion towards the wrist. Trials in which the participant pressed the incorrect response switch (11%) were discarded.

The effect of ISI on RT was very different for the three spatial relationships. For motion towards the shoulder (Fig. 2A) it is clear that in the Close-W condition, RT increased as a function of ISI while for the Close-S condition RT decreased with increasing ISI. For the largest ISI, the mean RT was smaller for the Close-S condition than for the Same condition. The opposite pattern of results was found for motion towards the participant's wrist (Fig. 2B). Experiment 1 data were analyzed using a 2×3×3 repeated measures ANOVA with motion direction, ISI and spatial offset as factors. There was a significant three-way interaction ($F_{(4,90)}=8.1$, $P<0.05$). An analysis of simple interactions (Keppel 1991) revealed significant ISI × Offset interactions for both directions of tactile motion (towards: $F_{(4,90)}=6.2$; away: $F_{(4,90)}=5.7$). Although the effect of offset direction was larger for simulated motion towards the shoulder (by 43 ms on average), an interaction contrast revealed this effect to be non-significant.

In previous experiments using static cueing the beneficial effect of a tactile cue on visual judgments fell off monotonically with the spatial separation between the visual target and the tactile cue (Driver and Spence 1998b). Therefore, if dynamic links between vision and touch *do not* exist, then we would predict that in the present study (1) RTs would always be faster for the Same condition and (2) there should be no difference between the RTs for the Close-S and Close-W conditions since the spatial separation between the tactile cue and visual target is equal in both conditions. From Fig. 2 it is clear that
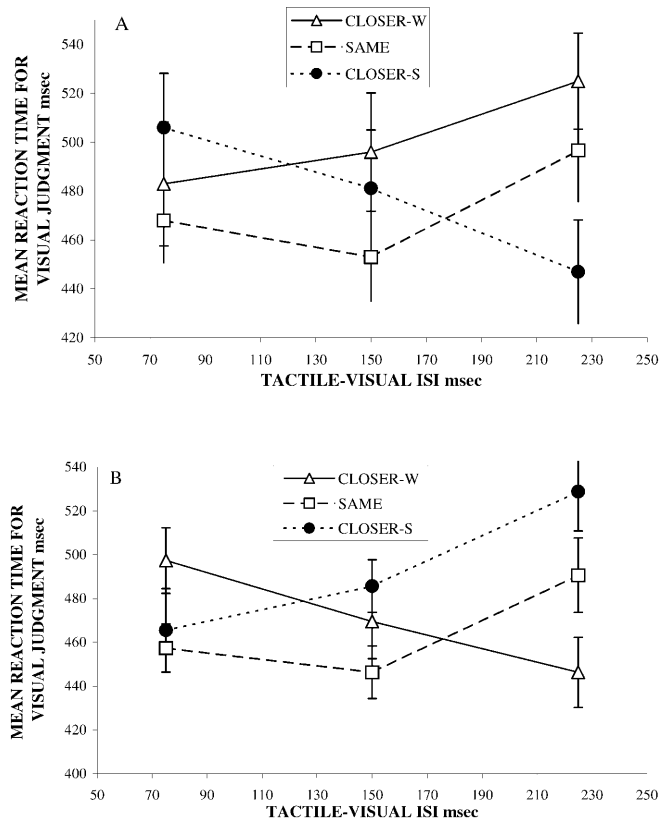
Fig. 2A, B Reaction times for judging the location of the visual target plotted as a function of the time between the last vibration in the tactile sequence and the onset of the LED. *Open triangles* are mean RTs for the condition where the illuminated LED was closer to the participant's wrist than the last vibration, *solid circles* are mean RTs for the condition where the illuminated LED was closer to the participant's shoulder than the last vibration, and *open squares* are mean RTs for the condition where the last vibration and illuminated LED were in the same spatial location. **A** Tactile motion towards the shoulder; **B** tactile motion towards the wrist. Data are averaged across the six participants. *Error bars* are standard errors

neither of these effects occurred. As ISI increased, *RTs were faster when the visual target was offset in the same direction as the tactile motion* than when the cue and target were in the same location. Furthermore, *RTs were up to 100 ms slower when the target was offset in the direction opposite to the tactile motion* compared to when the offset was in the same direction. These findings provide evidence that the crossmodal links between vision and touch are updated dynamically for moving objects.[1]

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[1] Previous research has identified two distinct types of reorienting in response to a peripheral cue. Overt reorienting involves moving the receptor surface towards the area of the cue (e.g., moving the eyes to foveate a light flash) while covert reorienting involves directing spatial attention to a peripheral location without moving the receptor. Since we did not monitor eye movements in the present study, it is possible that participants used an overt reorienting strategy of tracking the pattern of tactile motion with eye movements. However, previous research has shown that eye movements elicited by tactile stimulation are imprecise (Watanabe and Hashiba 1997). Therefore, it is unlikely the small differences in reaction time we observed are due solely to eye movements.

Another difference between the present findings and previous results using static cues is evident when we consider the effect of ISI on the Same condition. Spence et al. (1998) reported that RTs for a visual target preceded by a tactile cue in the same spatial location decrease monotonically up to ISIs of 300 ms, whereas in the present study RTs for the Same condition increased by roughly 40 ms when the ISI was increased from 150 to 225 ms. A possible explanation for this discrepancy could be that the simulated tactile motion caused inhibition of return for the Same condition at a much shorter ISI than has been found for static conditions (Spence et al. 2000).

In experiment 1 we found evidence that tactile motion can be used to reorient visual attention. In experiment 2 we examine the converse relationship: the effect of visual motion on the orienting of tactile attention.

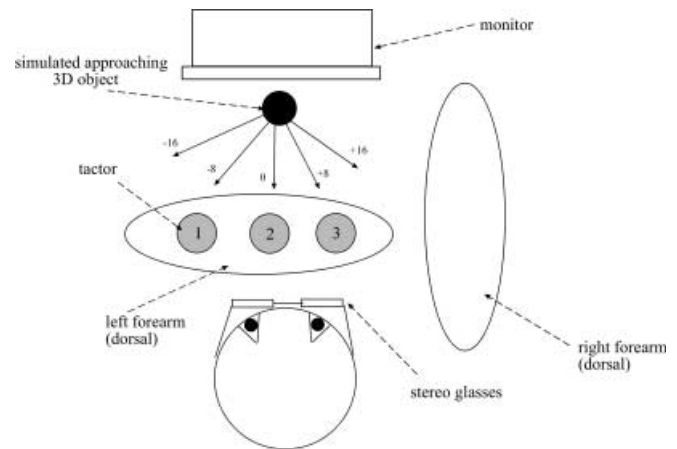## Experiment 2

Materials and methods

Five participants (three men and two women, all right handed) had a mean age of 26 years. All participants were naïve to the aims of the experiment. After explanation of the experimental procedures, participants gave informed written consent. The work was approved by the ethics committee at Nissan Cambridge Basic Research.

Apparatus and materials

In experiment 2, participants were seated at a table directly facing the computer monitor at a distance of 1 m. The headrest and headphones with white noise were again used. A schematic view of the experimental apparatus is shown in Fig. 3. The visual stimulus in this experiment was a simulated approaching sphere displayed on the monitor. Simulated motion towards the participant was created by increasing the angular size of the target and by changing its retinal disparity using LCD shutter goggles (CrystalEyes by Stereographics). See Gray and Regan (1998) for details of a similar simulation. The speed and direction of the motion were varied from trial to trial as described below. Tactile stimulation was produced by three vibrotactile stimulators (4 cm in diameter) strapped to the back of the participant's forearm. The tactors were mounted on the left arm for all participants. The vibrators were spaced 8 cm apart center-to-center. Tactors were driven by a train of square-wave pulses. The frequency of the pulse train was either 15 Hz or 30 Hz (chosen randomly) and the duration of each pulse train was 350 ms. Participants sat with their left arm resting on the table parallel to the monitor (see Fig. 3). Their arm was positioned so that the middle vibrator was in line with the center of the monitor. Their right hand rested on a response box with two microswitches.

Procedure

Each trial began with a 300-ms presentation of a central fixation cross. Two hundred milliseconds after the fixation cross disappeared, a simulated sphere that approached the participant's left arm was presented. The direction of motion-in-depth was chosen randomly from one of five possible directions as shown in Fig. 3: 0 cm (directly at the center tactor), +8 cm (directly at tactor no. 3), –8 cm (directly at tactor no. 1), +16 cm, –16 cm. The time to contact with the observer's arm (measured from the point in time when the object disappeared) was chosen randomly from one of

Fig. 3 Experiment 2 apparatus. The visual stimulus was a simulated approaching sphere presented on the computer monitor. Simulated motion towards the participant was created by increasing the angular size of the target and by changing its retinal disparity using LCD stereo glasses. The direction of simulated motion in depth was chosen randomly from one of five possible directions [shown with *arrows*: 0 cm (directly at the center tactor), +8 cm (directly at tactor no. 3), –8 cm (directly at tactor no. 1), +16 cm, –16 cm]. Tactile stimulation was produced by three vibrotactile stimulators (*gray circles*) strapped to the back of the participant's left forearm (numbered 1–3). The participant's forearm was oriented parallel to the monitor. The frequency of the vibration was either 15 Hz or 30 Hz. The location and frequency of vibration varied randomly from trial to trial. The participant's task was to press one of two switches using their right hand depending on whether the vibration frequency was high or low. See text for details

three values: 225 ms, 350 ms and 500 ms.[2] The time to contact was varied by changing the speed of the simulated approaching object while holding the presentation duration constant at 400 ms. A variable duration after the simulated object disappeared, one of the three tactile vibrators was turned on at either the high or low frequency. The location and frequency of vibration varied randomly from trial to trial. The participant's task was to press one of two switches depending on whether the vibration frequency was high or low. The trial terminated if no response had been made within 1,000 ms of tactor onset. The ISI between the disappearance of the sphere and the onset of the tactor was chosen randomly from one of three values (150 ms, 300 ms and 500 ms). There was a 500-ms interval between trials. Again it should be emphasized that the direction and speed of the simulated approaching object were uninformative to the participant's frequency judgment task. Each run consisted of 135 trials (3 time to contact values × 5 directions of motion × 3 tactor locations × 3 ISI values). Each participant completed 20 runs.

Results and discussion

Figure 4 plots mean RTs for the tactile frequency judgment averaged across the five participants. Trials in which the participant pressed the incorrect response key (12%) were discarded. To examine the relationship between the direction of motion of the visual target and the location of the tactor that was stimulated we first aver-

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[2] The distances of the virtual object from the participant's arm when the object disappeared were 0.36 m, 0.46 m and 0.56 m for the three times to contact respectively.
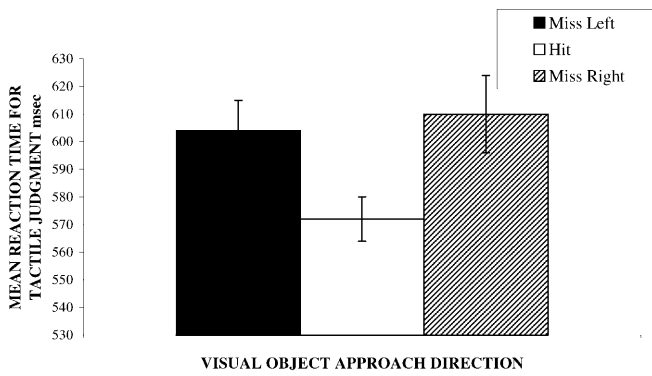
Fig. 4 Reaction times for the tactile frequency judgment plotted versus the direction of simulated visual motion. The *open bar* is the mean RT for conditions where the simulated visual motion was towards the location of the tactor that was stimulated; the *solid bar* is the mean RT for conditions where the visual motion was to the left (relative to the participant's view) of the stimulated tactor and the *hatched bar* is the mean RT for conditions where the visual motion was to the right of the stimulated tactor. Data are means for the five participants. *Error bars* are standard errors

aged grouped data for the following three conditions: (1) Hit – the direction of motion for the visual target coincided with the tactor that was stimulated (e.g., direction 0 and tactor 2 in Fig. 3), (2) Miss left – the direction of motion was offset to the left of the tactor that was stimulated (e.g., direction –8 or –16 and tactor 2) and (3) Miss right – the direction of motion was offset to the right of the tactor that was stimulated (e.g., direction +8 or +16 and tactor 2). It is clear from Fig. 4 that RTs were faster for the Hit condition than for either of the Miss conditions. A one-factor repeated measures ANOVA revealed a significant effect of approach direction on RT ($F_{(2,8)}$=10.6, P<0.01).

To further analyze the experiment 2 data we examined the effect of time to contact (TTC) of the approaching sphere on RTs for the tactile judgment. For this analysis we only used data from the Hit condition described above. Mean RTs for the different combinations of ISI and TTC are shown in Table 1. A 3×3 repeated measures ANOVA with ISI and TTC as factors revealed a significant interaction between ISI and TTC ($F_{(4,20)}$=42.0, P<0.001). As can be seen in Table 1, this effect occurred because the ISI associated with the fastest RT increased as a function of TTC[3] (i.e. minimum RTs fell along the diagonal of Table 1).

To summarize, the main effects found in experiment 2 were that (1) tactile frequency discrimination was faster when the simulated object approached the location of the vibration and (2) tactile frequency discrimination was faster when the tactile vibration occurred at roughly the point in time when the simulated moving object would

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[3] Because presentation duration was held constant, time to contact was perfectly correlated with the virtual distance of the approaching object at the point of disappearance. However, the finding that the maximal response enhancement occurred when TTC was roughly equal to ISI suggests that TTC is being used to reorient tactile attention rather than distance.

Table 1 Mean reaction times for the Hit condition in experiment 2 averaged across the five participants. Errors are standard errors

ISI (ms)	TTC (ms)		
	225	350	500
150	510 (32)	516 (30)	556 (29)
300	529 (30)	488 (35)	527 (31)
500	558 (29)	517 (30)	493 (29)

have been in the same spatial location as the vibrator (i.e., when the ISI was roughly equal to the TTC). These findings are again not consistent with a purely static link between vision and touch. Instead they suggest that predictive information from one sensory modality can be used by another modality. Specifically, our tactile map of external space can utilize direction and time to contact information from vision to reorient attention.

Do participants need to be able to see their arm for these tactile-visual interactions to occur? Recent imaging experiments have demonstrated that responses from multimodal brain areas decrease when participants cannot see the hand that is being stimulated (Macaluso et al. 2000). Within the visual modality, it has also been demonstrated that sight of one's hand leads to better estimates of time to contact when catching a ball (Savelsbergh and Whiting 1988). Therefore, we might expect the experiment 2 effects to decrease and become more variable when the arm is not visible to the participant.

General discussion

The results of the present study demonstrate strong dynamic links between vision and touch. In separate experiments we showed that dynamic tactile information can be used to accurately reorient visual attention and that dynamic visual information can be used to accurately reorient tactile attention. The phenomena reported here cannot be accounted for in terms of simple response biases since in each case the motion information was spatially uninformative to the participant's task (e.g., tactile motion up/down – visual judgment left/right).

The present findings would seem to be inconsistent with what is known about the response properties of multimodal neurons in the superior colliculus. Stein and Meredith have reported that these neurons have very coarse temporal and spatial tuning, a necessity so that minor shifts of the receptor organs can be tolerated. In superior colliculus neurons response enhancements occur for onset asynchronies ranging between roughly –200 ms (visual stimulus leads tactile stimulus) and +200 ms (Meredith et al. 1987). Conversely, in experiment 1 of the present study, we found both facilitation (i.e., speeded RTs) and inhibition over this same range depending on the direction of tactile motion (see Fig. 2). Similarly, in the spatial domain, Stein and Meredith found response enhancements when the stimulations

from the two modalities were separated by more than 50° (e.g., the receptive field size of the neuron). Conversely, in experiment 1 of the present study we found response inhibition for separations of only 10°.

These discrepancies suggest that the site for dynamic multimodal integration may be the cortex. Consistent with this proposal is the recent finding by McGlone and colleagues that cells in visual area MT (known to be responsive to complex patterns of visual motion) fire in response to tactile motion across the skin (Johansen-Berg 2001). Further, Colby et al. (1993) have reported that some cells in area VIP of the monkey intraparietal cortex respond to both tactile stimulation on the face *and* to visual stimuli approaching that particular location on the face. The results reported in experiment 2 of the present study are consistent with the properties of these VIP neurons; however, evidence for similar bimodal neurons that respond to skin locations on the arm has not been reported.

The present findings could have important implications for the design of multimodal human-machine interfaces (Spence and Driver 1997). If one sensory modality can use predictive information from another modality, it may be possible to create warning signals that provide more information than just crude spatial location. For example, one could imagine replacing an auditory buzzer that warns of an impending collision (e.g., in an aircraft or automobile) with a moving sound that has the same time to contact as the approaching object.

The present study provides evidence that our sensory systems can dynamically update the crossmodal links between the different modalities for moving objects such as an insect crawling down one's arm or an approaching ball. As mentioned above, the human brain is faced with the additional problem of remapping the registration between the senses when the observer moves (i.e., during self-motion). In future experiments we plan to investigate the integration of tactile and visual information for combinations of self-motion and object-motion.

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