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Visual Influences on Electrotactile Processing:
Localizing and Sequencing Crossmodal Interactions

by

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ABSTRACT

Visual Influences on Electrotactile Processing:
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Ruth M. Johnson

Most research studies on crossmodal processing of visual and tactile modalities have found that vision enhances touch. Nevertheless, it is unclear whether vision increases tactile sensitivity or changes participants’ response criteria for reporting touch. The following set of studies demonstrated that some experimental manipulations can lead to a small increase in tactile sensitivity; however, all experiments showed a consistently strong response bias to report feeling a touch with a concomitant visual stimulus. Further experiments sequenced the temporal processes associated with the visuotactile response bias and determined that greater visual influences on electrotactile processing occurred at smaller crossmodal asynchronies. A final experiment demonstrated that the reported electrotactile enhancement bias on light-present trials can be increased with transcranial magnetic stimulation (TMS) over the posterior parietal cortex 200 ms after visual and electrotactile stimuli presentation. Further research needs to be conducted to determine more precise cortical locations and temporal sequences of the crossmodal interactions between vision and touch.
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TABLE OF CONTENTS

Title Page i
Abstract ii
Acknowledgements iii
Table of Contents iv
List of Figures vi
Introduction 1

Previous Research (Visually Induced Feelings of Touch) 10
  Introduction 10
  Experiment 1 Results 11
  Experiment 2 Results 12
  Experiment 3 Results 13
  Experiment 4 Results 14
  Experiment 5 Results 14
  Discussion 15

Current Research 19
Experiment 6 21
  Method 21
  Results 24
  Discussion 31

Experiment 7 33
  Method 33
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Results</td>
<td>34</td>
</tr>
<tr>
<td>Discussion</td>
<td>42</td>
</tr>
<tr>
<td>Experiment 8</td>
<td>44</td>
</tr>
<tr>
<td>Method</td>
<td>44</td>
</tr>
<tr>
<td>Results</td>
<td>45</td>
</tr>
<tr>
<td>Discussion</td>
<td>48</td>
</tr>
<tr>
<td>Experiment 9</td>
<td>51</td>
</tr>
<tr>
<td>Method</td>
<td>51</td>
</tr>
<tr>
<td>Results</td>
<td>53</td>
</tr>
<tr>
<td>Discussion</td>
<td>65</td>
</tr>
<tr>
<td>General Discussion</td>
<td>67</td>
</tr>
<tr>
<td>References</td>
<td>76</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1: Experimental Apparatus and Visual and Tactile Stimuli 22
Figure 2: Experiment 6 Detection Results 26
Figure 3: Experiment 6 RT Results 28
Figure 4: Experiment 6 Signal Detection Results 30
Figure 5: Experiment 7 Detection Results 36
Figure 6: Experiment 7 Difference Results 37
Figure 7: Experiment 7 RT Results 39
Figure 8: Experiment 7 Signal Detection Results 41
Figure 9: Experiment 8 Detection Results 47
Figure 10: Experiment 8 RT Results 49
Figure 11: Experiment 9 Detection Results 56
Figure 12: Experiment 9 RT Results 60
Figure 13: Experiment 9 Signal Detection Results 64
Visual Influences on Electrotactile Processing:

Localizing and Sequencing Crossmodal Interactions

Introduction

Neural signals from the peripheral sensory receptors of different sensory modalities arrive in their respective primary sensory cortices at differing latencies. For example, when you see something graze your arm, the visual stimulus takes longer to reach the primary visual cortex compared with the concomitant tactile stimulus reaching the somatosensory cortex (Kandel, Schwartz, & Jessell, 2000). This study sought to determine how the brain then creates a uniform representation of the world. This set of experiments will furthermore examine the specific cortical locations and temporal sequences involved with crossmodal interactions between vision and touch in the brain. In the future, this research can be used to establish how crossmodal processing at later time periods could affect perception in unimodal cortical areas, such as somatosensory cortex, and visual cortices, as well as multimodal areas, such as the parietal cortex.

The parietal cortex has traditionally been seen as association or multimodal cortex, where different sensory modalities are integrated to form a cohesive representation of space (Critchley, 1953; Hyvarinen, 1982). Recent work has looked at the integration of visual, tactile, and proprioceptive information in the posterior parietal cortex. However, relatively few studies have investigated exactly where in the parietal cortex these interactions occur and the processing sequence involved. Numerous areas in the parietal cortex contribute to visual and tactile multimodal processing, even in primary sensory cortex. Functional neuroimaging studies in humans have demonstrated that the representation of the body surface can be imaged in somatosensory cortex with
reasonably high resolution (Johansen-Berg, Christensen, Woolrich, & Matthews, 2000; McGlone et al., 2002). These body representations are anatomically and functionally equivalent to somatotopically defined areas in SI of primates. Vision influences tactile processing, even in somatosensory cortex. For example, Zhou and Fuster (2000) recorded from primary somatosensory cortex while monkeys performed a visuo-haptic delay task, in which the monkeys were required to memorize a visual cue for a later tactile choice. Most of the cells that responded to the visual cue also responded to the haptic stimuli later. Zhou and Fuster concluded that these cross-modal associations between vision and touch were formed during the delay by associated visual stimuli activating neural networks representing tactile information. Another recent neurophysiological study showed that vision influenced somatosensory processing in primate area 5 (Graziano, Cooke, & Taylor, 2000). Graziano et al. (2000) had monkeys view simultaneous brushing of an artificial monkey hand and their own hidden real hand while recording cells from area 5 in the parietal cortex. Neuronal firing rates increased if the monkey’s real arm and the artificial arm were in the same location, which indicated that these parietal cells are involved with integrating visual and somatosensory information related to body locations.

A very important functional structure in the posterior parietal cortex is the intraparietal sulcus (IPS). Recent studies have focused on multimodal processing in the posterior parietal cortex, especially the IPS (for reviews, see Andersen, Snyder, Bradley, & Xing, 1997; Colby & Goldberg, 1999). Neurons in the anterior intraparietal (AIP) area of the IPS respond to visual stimuli that can be manipulated by the hand. Gallese, Fadiga, Fogassi, Luppino, & Murrato (1997) found that reversible inactivation of area
AIP in monkeys interfered with the ability to shape their hands appropriately for grasping an object. Visual guidance of hand movements has also been studied in humans using functional magnetic resonance imaging (fMRI) and implies an equivalency between human and primate AIP (Grefkes, Weiss, Zilles, & Fink, 2002). Grefkes et al. (2002) found significantly greater activation in human AIP when subjects were performing a task that required crossmodal transfer between visual encoding and tactile recognition of an object.

Immediate extrapersonal space is represented in the medial intraparietal (MIP) area of the IPS. Neurons in MIP are specialized for responding to stimuli within reaching distance (Colby & Goldberg, 1999). Colby and Duhamel (1991) found that monkey somatosensory neurons had receptive fields on the contralateral hand, while bimodal cells were optimally activated when the monkey reached for a visual target. Purely visual neurons also had an interesting property where they increased their firing rates when a visual target was moved within reaching distance. Colby and Duhamel concluded that cells in MIP contributed to the spatial representation necessary for limb movement. Similar results were obtained in an fMRI study that showed increased hand movement related activation in the human MIP during grasping and pointing tasks (Simon, Mangin, Cohen, Bihan, & Dehaene, 2002). Simon et al. (2002) concluded that the MIP area was specialized for visually guided hand movements.

Neurons in the ventral intraparietal (VIP) area of the IPS are excited by visual and tactile stimuli and contribute to a polymodal representation of space. The receptive fields of tactile stimuli in VIP usually involve the face, but some also cover the hands and limbs (Carey, 2000). The visual receptive fields of bimodal neurons in VIP are restricted to the
space around the tactile receptive field (Bremmer, Duhamel, Hamed, & Graf, 1997; Duhamel, Colby, & Goldberg, 1998). Furthermore, neurons in monkey VIP that had congruent tactile and visual receptive fields also had similar preferred directions of motion (Bremmer et al., 1997, Duhamel et al., 1998). In a functional neuroimaging study, Bremmer, Schlack, Duhamel, Graf, & Fink (2001) measured hemodynamic responses to visual, tactile, and auditory moving stimuli compared to stationary controls. Bremmer et al. (2001) found increased activity evoked by all three stimuli in the human VIP area of the intraparietal sulcus. Therefore, neurons in VIP are responsible for detecting and processing polymodal spatial and motion information to objects in near personal space in both humans and monkeys (Bremmer et al., 2001).

The parietal cortex is involved in several diverse functions, and patients with brain damage in the parietal cortex display a wide range of symptoms. Patients with lesions in the parietal lobe (especially on the right hemisphere) often exhibit disorders such as visuo-spatial disorientation, unilateral neglect, and extinction (Hyvarinen, 1982). Patients with extinction fail to notice a previously detectable contralesional stimulus when a competing ipsilesional stimulus is presented simultaneously. Recent studies have shown that cross-modal extinction interactions for visual and tactile stimuli can be modulated depending on vision of the hand being touched (Ladavas, di Pellegrino, Farne, & Zeloni, 1998; Ladavas, Farne, Zeloni, & di Pellegrino, 2000). In both these studies, patients with tactile extinction failed to report any contralesional (left) tactile stimuli when a visual stimulus was presented near the ipsilesional (right) hand. However, this crossmodal extinction effect only occurred when patients saw their hands. When the right hand was covered, the crossmodal extinction effect caused by a light presented near
the left hand significantly decreased. Ladavas et al. (2000) concluded that their results could be explained by referring to the bimodal neurons in the intraparietal sulcus of the parietal cortex that coded for visual and somatosensory space around the hand.

The previously described monkey, patient, and neuroimaging studies demonstrate that incoming visual and tactile stimuli are combined in the posterior parietal cortex. These studies also reveal that the incoming visual sensations usually preferentially influence somatosensation. This visual influence on tactile and proprioceptive processing has been shown in behavioral studies using neurologically normal individuals as well.

Several studies have looked at visual influences on normal proprioceptive processing. Stratton (1897) described his own personal visual adaptation to inverting optical lenses. When he first put the inverting lenses on, the world appeared shockingly different and Stratton had trouble functioning in his new visual environment. But after several days of wearing the lenses, he began to adapt and function in his new environment. Adaptation to reversed vision has also been studied recently (Sekiyama, Miyauchi, Imaruoka, Egusa, & Tashiro, 2000). Subjects who wore left-right reversing lenses for over a month not only adapted to their new environment, but could eventually utilize both their new and old representations. Several times during the month, the participants completed a left and right hand identification task during functional magnetic resonance imaging (fMRI). For the first two weeks, the participants were almost never correct, but after three weeks the subjects became much better at the task. Sekiyama et al. (2000) concluded that adaptation to perceived object locations in space corresponded with the appearance of the new hand representation. Experiments in the 1960s investigated visual influences on normal proprioceptive processing. Several studies
investigated visual adaptation to displaced images (Harris, 1963; Held & Freedman, 1963). Subjects completed an initial reaching task while their arms were hidden, then prisms were placed on the subjects and they viewed their arms while reaching (Harris, 1963). When vision and proprioception provided conflicting information, subjects relied on visual input when completing the reaching tasks while wearing the prisms. Furthermore, after they adapted to the visual displacement, participants incorrectly pointed at positions in space when the prisms were removed and accurate vision was restored (Harris, 1963). The previously described studies demonstrated that the proprioceptive system relied on and adapted to the visual environment, especially when vision and proprioception provided conflicting sensory information.

Furthermore, the visual system tends to dominate when visual and tactile processing provide conflicting information as well. When participants looked through a horizontal-minifying lens into a box, they saw a small rectangle lying on a piece of black cloth (Rock, Mack, Adams, & Hill, 1965; Rock & Victor, 1964). At the same instant they looked through the minifying lens, subjects simultaneously grasped the object (which was actually a square) from underneath. The black cloth prevented participants from viewing their hands, which ensured that visual contextual cues would not influence their decisions about the shape of the object. When asked to draw the object, subjects drew a rectangle, which confirmed that they were not aware of the perceptual conflict and simply relied on visual cues. These studies demonstrated that touch perception adapted to the dominant visual system so that participants never detected a conflict. In a recent study, Ro, Wallace, Hagedorn, Farnè, and Pienkos (2004) also demonstrated that inducing a conflict between vision and touch increased touch detection. Transcranial
magnetic stimulation (TMS) over the posterior parietal cortex then disrupted normal processing and eliminated the visual increase in tactile perception after the conflict.

Further research on normal subjects has studied how vision can augment tactile perception. Using a video camera, participants viewed their hand on a monitor in front of them, so that proprioceptive orienting of the head was prevented (Tipper et al., 1998). Tactile perception was facilitated with vision of the hand, independent of proprioception of the head. In a follow-up study using a video camera and monitor again, vision influenced tactile detection at body sites that could not be directly viewed by the participants, such as the face or the back of the neck (Tipper et al., 2001). The effect of non-informative vision on tactile spatial resolution has also been investigated (Kennett, Taylor-Clarke, & Haggard, 2001). Participants were significantly better at a two-point discrimination task when their arm was visible, compared to when the arm was not visible or when viewing a neutral object. Tactile perception was further increased with magnification of the participant’s arm. Using event-related potentials (ERPs), Taylor-Clarke, Kennett, and Haggard (2002) furthermore suggested that vision might modulate tactile processing in the somatosensory cortex via back projections from multimodal posterior parietal areas. Johnson, Burton, and Ro (2006) also demonstrated that touch detection improved when a threshold level electrotactile stimulus was simultaneously paired with a non-informative visual stimulus. In addition, subjects exhibited a response bias to report touches more often when a visual stimulus was presented without a corresponding tactile stimulus.

Recently, patient studies have specifically looked at the visual enhancement of touch perception. Halligan, Hunt, Marshall, & Wade (1996) reported a right hemisphere
stroke patient who detected all contralesional tactile stimuli when he viewed his left hand being touched, but felt nothing when he could not see the touch. When the patient could not see his hands, however, he could still reliably transfer information from his impaired hand (which he did not know was being touched) to his normal hand. However, when the patient watched a previously taped video of his hand being touched, he also reported feeling touches even when no tactile stimuli were delivered. Halligan et al. (1996) suggested that the correlated visual information increased the patient’s subthreshold touch sensations into consciousness. Another case study investigated a patient whose tactile detection of a light tap was also improved by the sight of a non-informative flash of light on a rubber hand placed directly above the patient’s own concealed hand in the same orientation (Rorden, Heutink, Greenfield, & Robertson, 1999). When a salient, but non-predictive light was attached to the rubber hand, the patient’s touch perception was enhanced compared to when the light was in the same location but on an experimenter’s hand that was oriented inconsistently with respect to the patient’s hand. Rorden et al. (1999) concluded that the presence of the light on the rubber hand dramatically increased tactile perception because the patient viewed the rubber hand as being his own, but did not feel that way towards the experimenter’s hand.

The visual cortex has also been found to be necessary for normal tactile perception (Zangaladze, Epstein, Grafton, & Sathian, 1999). While participants distinguished between vertical and horizontal gratings, transcranial magnetic stimulation (TMS) was performed over the occipital cortex. TMS disrupted normal functioning of the visual cortex and interfered with subjects’ ability to discriminate the tactile orientations.
The previously described studies demonstrate that visuotactile processing is complicated and distributed over several areas of the brain. The following set of experiments sought to examine crossmodal processing of visuotactile interactions. This study determined that participants were more likely to report feelings of touch when a concomitant light was presented, even on trials where the electrotactile stimulus was not delivered. However, this visual enhancement of touch was not due to an increase in subjects' sensitivity, but rather a response bias to report touch with vision, as shown in the following study (Johnson et al., 2006).
Previous Research

Research Report

Visually induced feelings of touch

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ABSTRACT

Recent studies have reported that vision can enhance tactile perception, even in patients with somatosensory deficits. However, it is unclear in these previous studies whether visual input truly enhances detection of tactile stimuli or induces a higher propensity for reporting touch by changing response criteria. In this study, we demonstrate in neurologically normal subjects that in addition to small increases in tactile sensitivity when a non-informative, suprathreshold visual stimulus is presented, there are highly consistent changes in response criteria for reporting touch with vision, even when no tactile stimulus is delivered. These results suggest that some of the previously reported enhancements of touch from vision may rather be a consequence of strategic sensory encoding processes that rely upon the typical correlations between multisensory events.

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1. Introduction

All of our incoming sensations help to build our perception of the world. However, vision appears to be our most important and relied on sensory modality, typically dominating or altering our other senses. For example, several studies have demonstrated that other senses adapt to a distorted visual image (Harris, 1963; Sekiyama et al., 2000; Stratton, 1897). These studies show that the proprioceptive system adapts to the visual environment, especially when vision and proprioception provide conflicting sensory information. When visual and tactile processing provide conflicting information, the visual system not only dominates but can also alter touch perception (Pavan et al., 2000; Rock and Victor, 1964, 1965; Ro et al., 2004). For example, using a mirror to induce a conflict between vision and touch, Ro et al. (2004) enhanced tactile perception for several minutes and established that this visual enhancement of touch induced by the conflict occurs in the posterior parietal cortex.

Other research has also shown that vision can augment tactile perception, even in cases without any influences from proprioceptive orienting (Kennett et al., 2001; Taylor-Clarke et al., 2002; Tipper et al., 1998, 2001). In one study, for example, Tipper et al. (1998) used a video camera to display a participant's hand on a monitor placed directly in front of the subject and demonstrated that tactile perception was facilitated (i.e., response times were faster) with vision of the hand, independent of proprioception of the head. In a follow-up study, vision influenced tactile detection at body sites that could not be directly viewed by the participants, such as the face or the back of the neck (Tipper et al., 2001). The effect of non-informative vision on tactile spatial resolution has also been investigated (Kennett et al., 2001). Participants were significantly better at a two-point discrimination task when their arm was visible, compared to when the arm was not visible or when viewing a neutral object. Tactile perception was further increased with magnification of the participant's arm. Using event-related potentials (ERPs), Taylor-Clarke et al. (2002) suggested that vision of a to-be-touched body part might modulate tactile processing in the somatosensory cortex via back projections from multimodal posterior parietal areas.

Based on the multisensory facilitation depicted in the previous experiments, some patient studies have investigated...
whether vision can systematically enhance touch perception. In one study, Halligan et al. (1996) reported a right hemisphere stroke patient who detected all contralesional tactile stimuli when he viewed his left hand being touched, but felt nothing when he could not see the touch. When the patient could not see his hands, however, he could still reliably transfer information from his impaired hand (which he did not know was being touched) to his normal hand. Importantly, in relation to the current study, when the patient watched a previously taped video of his hand being touched, he also reported feeling touches even when no tactile stimuli were delivered. Halligan et al. (1996) suggested that correlated visual information decreased the patient's threshold for touch sensations, but it remains unclear why the patient made false reports of touch under some conditions.

Rorden et al. (1999) investigated another patient whose tactile detection of a tap was also improved by the sight of a non-informative flash of light on a rubber hand placed in the same orientation directly above the patient's own concealed hand. When a salient, but non-predictive light, was attached to the rubber hand, the patient's touch perception was enhanced compared to when the light was in the same location but on the hand of an experimenter who was sitting across from the patient. On light-only trials, when the visual but not the tactile stimulus was presented to the patient, his false alarm rates were very low and did not differ between the rubber hand and experimenter hand conditions. Rorden et al. (1999) concluded that the presence of the light on the rubber hand dramatically increased tactile sensitivity because the patient viewed the rubber hand as being his own but did not feel that way towards the experimenter's hand.

Based on the two previously described patient studies, it is unclear whether visual input consistently enhances tactile perception or changes response biases. Since we have lifelong experiences of visual input correlated with touch, perhaps response biases operate to induce feelings of touch even when no tactile stimulus is present, such as when seeing an insect induces a sensation of something crawling on one's skin. Therefore, we tested whether a non-informative simultaneous visual stimulus can increase threshold-level tactile perception in neurologically normal subjects, with or without associated changes in response biases. We hypothesized that a response bias would raise both the reported detection of touch when a simultaneous but non-predictive flash of light is presented with the tactile stimulus and would also increase errors in reporting touch when a light is presented alone. Using analyses based on Signal Detection Theory (Macmillan and Creelman, 1991), we examined whether the presence of a visual stimulus enhances detection and/or changes response criteria.

2. Results

Five experiments determined that non-informative visual information not only modulated near-threshold touch perception but consistently induced shifts in biases for reporting touch with vision. In each experiment, tactile stimulation was delivered to subjects' hands through ring electrodes attached to their middle fingers. A small red LED was also taped to the ring electrodes and was illuminated for 5 ms when serving as the visual stimulus (Fig. 1).

2.1. Experiment 1 results

Experiment 1 used a non-informative light simultaneously paired with a near-threshold tactile stimulus in the critical condition to determine whether it would influence touch detection and response biases. The experiment had four conditions that were presented equally often and in a randomized order throughout the experiment: (1) Light trials; (2) Touch trials; (3) Both light and touch trials; and (4) Catch trials on which no sensory stimulation was delivered to the subject. The subjects' task was to state whether they saw a light, felt a touch, perceived both, or detected nothing. Responses were considered correct if the participants accurately reported all stimuli administered on a particular trial or reported 'none' on the Catch trials. Trials on which subjects were given a Catch trial and responded "touch" or were given a Light trial and responded "both" were considered false alarms.

Fig. 1 – The apparatus and stimuli used in Experiments 1, 2, and 3 are shown. Experiment 4 had a second set of ring electrodes and another LED attached to a participant's left index finger, while Experiment 5 had the ring electrodes and LED attached to the participant's right middle finger.
The mean percentages of hits and false alarms averaged across light-present and light-absent trials are shown in Table 1. Tactile detection rates increased 6.9% during Both trials compared to Touch trials (Fig. 2a). Participants reported that they felt the tactile pulse significantly more often when it was paired with the light than when presented alone, t(23) = 2.22, P = 0.037, two-tailed. Although the 2.1% increase in false alarms was in the expected direction, with more false alarms for reporting touch during Light trials than with Touch trials, the difference did not achieve significance, t(23) = 1.44, P = 0.162, two-tailed (Fig. 2b). Other types of incorrect responses occurred on less than 1% of trials and therefore were not included or further analyzed.

We also utilized signal detection procedures to calculate d' and c (Macmillan and Creelman, 1991). Changes in sensitivity were measured using d': d' = (Z(Hits)тегеніз/false alarms)), while changes in criterion, a measure of response bias (Macmillan and Creelman, 1991), were measured using c = -(Z(Hits)тегеніз/false alarms)) / 2). Eight out of 24 subjects did not commit a false alarm in either the Light or Touch trials. False alarm rates were estimated for these participants to allow for signal detection analyses by dividing 0.5 by the number of trials in the experiment (Stanislaw and Todorov, 1999). Average d' and c values by condition are shown in Table 1. In Experiment 1, differences in d' were not significantly different between the Both and Touch conditions, t(23) = 0.859, P = 0.399, two-tailed (Fig. 3). However, their c values significantly decreased in the Both trials compared to the Touch trials, t(23) = 2.39, P = 0.025, two-tailed (Fig. 3). This decrease in criterion value reflects a more liberal response bias, with subjects more likely to report feeling a tactile pulse when a visual stimulus was presented. This criterion shift when a light was present contributed to the higher percentage of detection rates in the Both vs. Touch trials and in the Light vs. Catch trials. Rather than an increase in tactile sensitivity when a light was simultaneously presented with a pulse, the criterion for reporting a pulse was lowered when the light was present. This criterion shift contributed to at least some of the significant percentage increase in reporting the pulse.

### Table 1 - The percentages of mean hits and false alarms are shown for Experiments 1-5, as well as d' and c values for Experiments 1-3

<table>
<thead>
<tr>
<th>Light Present</th>
<th>Hits (%)</th>
<th>FA (%)</th>
<th>d'</th>
<th>c</th>
<th>Light Absent</th>
</tr>
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<tr>
<td>Expt 1</td>
<td>83.2</td>
<td>6.9</td>
<td>1.97</td>
<td>0.61</td>
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</tr>
<tr>
<td>Expt 2</td>
<td>57.1</td>
<td>7.5</td>
<td>1.76</td>
<td>0.89</td>
<td>46.9</td>
</tr>
<tr>
<td>Expt 3</td>
<td>59.6</td>
<td>6.3</td>
<td>1.91</td>
<td>0.69</td>
<td>46.8</td>
</tr>
<tr>
<td>Expt 4</td>
<td>77.0</td>
<td>10.9</td>
<td>N/A</td>
<td>N/A</td>
<td>61.4</td>
</tr>
<tr>
<td>Expt 5</td>
<td>80.9</td>
<td>34.2</td>
<td>N/A</td>
<td>N/A</td>
<td>74.0</td>
</tr>
</tbody>
</table>

N/A - not applicable; sensitivity and response criteria were not calculated on the discrimination data from Experiments 4 and 5.

* Catch trials on which no sensory stimulation was given did not occur in Experiment 4. The reported false alarm rate is an average of Light trials when subjects reported feeling a touch on the opposite finger from the one with the visual stimulus and Touch trials when subjects reported feeling a touch on the opposite finger from the one that was stimulated.

* The false alarm rates for Experiment 5 occurred when subjects reported feeling a touch on the hand where a light was presented during trials where the visual and tactile stimuli were delivered to opposite hands or when they report a touch on the opposite finger from the one that was stimulated. The false alarm rates are considerably higher than in the previous four experiments because participants were forced to choose.

2.2. Experiment 2 results

The second experiment examined whether pairing supra-threshold association trials before the experiment would help...
to further improve detection beyond any change in response bias during both trials. Experiment 2 was identical to Experiment 1, except that subjects were given association trials with suprathreshold pairings of light and touch at the beginning of the experiment. After the initial suprathreshold pairing phase, the tactile stimuli were returned to threshold levels by the experimenter, and the experiment followed the same format as Experiment 1.

Mean percentages for hits and false alarms by condition are shown in Table 1. After the association trials, tactile detection rates increased 10.2% during both trials compared to Touch trials (Fig. 2a). Participants reported that they felt the touch significantly more often when it was paired with the light in both trials than when the touch was presented alone, t(23) = 3.04, P = 0.006, two-tailed. Subjects also incorrectly said "both" more often during Light trials than they said "touch" during Catch trials. This 5% increase in false alarms was significant, t(23) = 3.21, P = 0.004, two-tailed (Fig. 2b). Eleven out of 24 subjects did not commit a false alarm in either the Light or Catch trials.

Average d' and c values by condition are shown in Table 1. In Experiment 2, the difference in d' was not significant between the Both and Touch conditions, t(23) = 1.01, P = 0.322, two-tailed (Fig. 3). However, their c values did significantly decrease in the Both trials compared to the Touch trials, t(23) = 4.07, P < 0.001, two-tailed (Fig. 3). Again, this decrease in response criterion revealed a response bias, with participants significantly more likely to report feeling a touch when a visual stimulus was presented, regardless of whether the tactile pulse was actually delivered.

2.3. Experiment 3 results

In contrast to the first two experiments, the instructions in Experiment 3 strongly emphasized reporting every tactile sensation subjects felt on their left middle fingers, even when they were not sure it was the pulse. These instructions were intended to induce the same bias for reporting touch across all conditions, thus, false alarms were expected to be higher in this experiment for both reports of "touch" during Catch trials and "both" during Light trials. This manipulation was introduced to determine whether inducing a general bias towards reporting touch might increase sensitivity to touch on the Both compared to the Touch trials.

Table 1 shows the mean percentages of hits and false alarms by condition. Tactile detection rates increased 5.8% during the Both trials compared to the Touch trials (Fig. 2a). As in the previous two experiments, participants reported that they felt the touch significantly more often when it was paired with the light than when presented alone, t(23) = 3.59, P = 0.001, two-tailed. While false alarm rates were higher overall in Experiment 3, the 2.3% increase in false alarms did not significantly differ between Light trials on which subjects said "both" and Catch trials on which they said "touch", although it was again in the expected direction, t(23) = 1.72, P = 0.099, two-tailed (Fig. 2b). Five out of 24 subjects did not commit a false alarm in either condition, despite the emphasis in the instructions.

Average d' and c values by condition are shown in Table 1. In Experiment 3, d' values were higher in the Both compared to the Touch condition, although this difference fell just short of significance, t(23) = 1.971, P = 0.061, two-tailed (Fig. 3). Consistent with the previous experiments, c values significantly decreased in the Both trials compared to the Touch trials, t(23) = 3.38, P = 0.003, two-tailed (Fig. 3). This significant decrease in criterion revealed a more liberal response bias for Light trials, with subjects more likely to report feeling a tactile pulse when a visual stimulus was presented.

2.4. Between experiment analyses for the detection experiments

Because these first three experiments were very similar and subjects responded in the same way, we also tested whether any overall differences existed between Experiments 1, 2, and 3. A 2 (condition) x 3 (experiment) ANOVA was conducted on d' measurements of sensitivity with condition (Both and Touch trials) as the within-subject variable and experiment (1, 2, and 3) as the between-subject variable. There was a main effect of condition with significantly higher d' values for the Both trials compared to Touch trials (F(1,69) = 4.64, P = 0.035). Neither the main effect of experiment (F(2,69) = 0.358, P = 0.757) nor the condition by experiment interaction (F(2,69) = 0.234, P = 0.792) was significant. These results demonstrate that participants display a small increase in sensitivity when a light was present during the Both trials compared to the Touch trials (Fig. 3). Another 2 (condition) x 3 (experiment) ANOVA was conducted on c measurements of response bias with condition (Both and Touch trials) as the within-subject variable and experiment (1, 2, and 3) as the between-subject variable. There was a main effect of condition with significantly lower c values for the Both trials compared to Touch trials (F(1,69) = 32.2, P < 0.001). The main effect of experiment (F(2,69) = 1.19, P = 0.320) and the condition by experiment interaction (F(2,69) = 0.719, P = 0.491) were not significant. This analysis confirmed that participants decreased their criterion levels when a visual stimulus was present on a given trial and induced a significant response bias (Fig. 3). Because responses on both trials also reflected a more liberal response criterion level, their hit rates as well as their false alarm rates as measured by percent change significantly increased when a light was present. The signal detection analysis established that the presence of a non-informative light had a small influence on tactile sensitivity overall, but a much greater and consistent effect on participants' response biases, regardless of whether a tactile pulse was presented simultaneously or not.

The previous three experiments used a detection paradigm to examine the effects of a visual stimulus on tactile sensitivity and found that the presence of a non-informative light increased participants' reported sensation of touch, independent of tactile stimulation. Furthermore, signal detection analyses showed that this reported difference was due to a significant response bias to report feeling a touch when a light was presented simultaneously, as well as a small and less consistent increase in sensitivity overall when a light was presented. In the next two experiments, we used discrimination tasks to determine if similar effects could be obtained when vision and touch were delivered to different fingers. The discrimination paradigms were designed such that signal
detection analyses would not be necessary to determine the differential influences of changes in sensitivity and response criteria for the remaining two experiments.

2.5. Experiment 4 results

Experiment 4 examined visual influences on tactile processing across two adjacent fingers and was designed to determine whether a light presented on a different finger from the tactile pulse had the same effect on touch perception as when both the visual and tactile stimuli were presented simultaneously on the same finger. The experiment differed from the previous three experiments in experimental design, instructions, and number of trials. Experiment 4 was similar to Experiments 1–3, except that this experiment used visual and tactile stimuli that were presented to the subjects’ left index and middle fingers and required a location discrimination response. Tactile thresholds were set near 60% detection (rather than 50% as in previous experiments) because of the more difficult localization task used in this experiment. Experiment 4 had four conditions that were presented equally often and in randomized order to each finger: (1) Light trials; (2) Touch trials; (3) Both light and touch trials on the same finger; and (4) Both light and touch trials on different fingers. The participant’s task was to state the finger (if any) on which the tactile pulse was felt on each trial. Responses were considered correct only if the participant accurately reported the finger on which the tactile stimulus was given or reported ‘none’ on the Light trials. False alarms occurred when subjects stated they felt a pulse on the opposite finger from the one actually touched or when they reported feeling a touch on a Light trial. Subjects were asked to look at their left hand so they could see the visual stimulus but were not required to report any visual information. In this way, the visual stimulus in this experiment was truly non-informative and unrelated to the participants’ task.

The fourth experiment established what effect a light presented on a different finger from the tactile pulse had on touch perception compared to when both the visual and tactile stimuli were presented simultaneously on the same finger. Mean percentages of hits and false alarms by condition are shown in Table 1. Correct tactile response rates increased 15.6% on Both trials presented to the same finger compared to Touch alone trials (Fig. 2a). Participants reported that they felt the tactile pulse significantly more often when it was paired with the light on the same finger than when it was presented alone, t(23) = 7.50, P < 0.001, two-tailed. Correct tactile response rates also significantly increased by 12.3% during Both trials delivered to the same finger compared to Both trials delivered to different fingers, t(23) = 4.79, P < 0.001, two-tailed. Furthermore, accuracy rates did not significantly differ between Touch trials (61.4%) and Both trials (64.7%) when the visual and tactile stimuli were delivered to different fingers, t(23) = 1.17, P = 0.256, two-tailed. Thus, the visual stimulus presented on the opposite finger did not increase reports of tactile sensations above the baseline rates detected in the Touch trials. However, the visual stimulus did influence false alarm rates (Fig. 2b). False alarms occurred when subjects reported feeling a touch on a Light trial or stated they felt a pulse on a different finger than the one that was stimulated for Both and Touch trials. Because Experiment 4 did not have Catch trials where no sensory stimulation was given, the baseline false alarm rate was calculated by averaging Light trials when subjects reported a touch on the finger opposite the visual stimulus (5.1%) and Touch trials when participants felt the pulse on a different finger from the one that was stimulated (5.5%). The two baseline false alarm measures were not significantly different, t(23) = 0.480, P = 0.635, two-tailed, and were therefore averaged (5.3%) and used for the remaining analyses. Participants incorrectly reported feeling more tactile pulses on the finger where the visual stimulus was present during Light trials compared to the averaged baseline false alarm rate, this 5.6% increase in false alarms was significant, t(23) = 3.75, P = 0.001, two-tailed (Fig. 2b). In addition, subjects also incorrectly reported feeling more touches (8.5%) on the finger where the light flashed in the Both trials when visual and tactile stimuli were given to different fingers compared to the baseline false alarm rate, t(23) = 3.95, P = 0.001, two-tailed.

2.6. Experiment 5 results

Experiment 5 examined visual influences on tactile processing across participants’ hands and was designed to determine whether a light presented on a different hand from the tactile pulse had the same effect on touch perception as when both the visual and tactile stimuli were presented simultaneously to the same hand. Experiment 5 used a discrimination paradigm and was similar to Experiment 4, except that in this experiment, the visual and tactile stimuli were presented to the subjects’ middle fingers on the left and right hands. Experiment 5 had three conditions that were presented equally often and in randomized order to both hands throughout each experiment: (1) Touch trials; (2) Both light and touch trials, with both stimuli presented simultaneously to the same finger; and (3) Both light and touch trials, with the stimuli presented on opposite hands. The participants’ task was to report the hand on which the tactile pulse was delivered. Responses were considered correct only if participants accurately reported where the tactile stimulus was delivered. False alarms occurred when subjects stated they felt a pulse on the opposite hand from the one actually stimulated. Similar to Experiment 4, subjects did not have to report where they saw the visual stimulus, and therefore, it was truly non-informative and unrelated to the participants’ task.

Mean percentages of hits and false alarms by condition are shown in Table 1. Correct reports of tactile stimulation increased 6.9% in Both trials with vision and touch on the same finger compared to Touch alone trials (Fig. 2a). Participants reported that they felt the tactile pulse significantly more often when it was paired with the light on the same hand than when it was presented alone, t(23) = 3.18, P = 0.004, two-tailed. Furthermore, accuracy rates significantly decreased 8.2% in Both trials when the visual and tactile stimuli were delivered to opposite hands compared to Touch trials, t(23) = 3.06, P = 0.006, two-tailed. Thus, the visual stimulus
presented on the opposite hand from the tactile stimulus increased reports of tactile sensations on the hand where the light was given instead of on the hand where the pulse was delivered. Therefore, the visual stimulus not only increased sensitivity but also induced subjects to commit more false alarms.

3. Discussion

The experiments described in this study demonstrate that a non-informative visual stimulus influences the reported perception of touch in neurologically normal subjects by weakly enhancing sensitivity, as well as creating a strong response bias. In all five experiments, participants were significantly more likely to respond that they felt a touch when both the visual and tactile stimuli were presented simultaneously to the same finger than when the touch was presented alone. Furthermore, in Experiments 1–3, subjects also reported feeling more touches on trials when only a light was presented compared to trials when nothing was presented. Unlike this robust and reliable response bias effect, the effect of the simultaneous presentation of the light on actual sensitivity to tactile pulses was much smaller and was only significant in the between experiment analysis.

The fourth experiment further demonstrated that accurate reports of tactile stimulation increased only when the visual and tactile stimuli occurred simultaneously on the same finger and not when the light was delivered to the other finger, demonstrating the specificity of these effects. In fact, accuracy when the light and touch were on opposite fingers was similar to accuracy on Touch only trials presented to one finger. In addition, the visual stimulus influenced subjects’ touch perception and caused them to report false alarms in two different ways. Participants reported feeling the tactile pulse more often on Light trials compared to the baseline trials. Furthermore, when the visual stimulus was presented to the opposite finger from the tactile stimulus, false alarm rates were significantly higher with more reports of feeling the pulse on the finger where the light had flashed compared to the baseline rate. Experiment 5 had similar results as Experiment 4, except that when subjects were forced to choose where they had felt the pulse and a tactile stimulus was delivered on each trial, they were heavily influenced by the light when it was presented to the opposite hand from the touch. Participants incorrectly made more false alarms when visual and tactile stimuli were delivered to opposite hands and reported feeling the touch on the hand where the light had been presented in the fifth experiment.

Response criterion was significantly lower in the both trials compared to the Touch trials in the first three experiments. This criterion shift contributed to the significant increases in hit rates during the both trials compared to the Touch trials and in false alarm rates during the Light trials compared to the Catch trials, highlighting the importance of using signal detection measures to compute bias-free changes in sensitivity. Probabilistically, the lower criterion during trials when a light was presented would result in a greater increase in accuracy during both trials than in false alarms during Light trials (Stanislaw and Todorov, 1999), as was found across the three detection experiments. Thus, although the effects of a response bias may appear small because a substantial proportion of participants never produced any false alarms, it nonetheless clearly influences the report of a touch when visual information is provided.

Several other recent studies have shown how vision can facilitate tactile processing in normal participants (e.g., Kennett et al., 2001; Pavani et al., 2000; Ro et al., 2004; Taylor-Clarke et al., 2002; Tipper et al., 1998, 2001). However, these studies all used body parts as a significant component in their experimental designs. The visual stimulus in our experiment was placed on the finger so that the visual and tactile stimuli would occur in the same location; however, we did not manipulate body part viewing or the visual stimulus. The light in our experiments was non-informative and did not predict if (or where in Experiments 4 and 5) a tactile pulse would occur. In addition, in Experiments 4 and 5, participants were not even required to report anything about the light, yet it still had an effect on their touch perception. These results, therefore, are the first to demonstrate that this increased accuracy in reporting tactile stimulation with vision is largely due to a response bias when the visual stimulus is truly non-informative. Furthermore, none of the previous studies analyzed their results using signal detection procedures (Kennett et al., 2001; Pavani et al., 2000; Ro et al., 2004; Taylor-Clarke et al., 2002; Tipper et al., 1998, 2001) and therefore could plausibly have reflected shifts in criterion in addition to (or rather than) changes in sensitivity.

In a similar experiment studying visual and auditory multisensory processing, Lovelace et al. (2003) showed that a simultaneous non-informative light enhanced the report of a sound. In the first experiment, they found that the hit rate of low-intensity sounds, as well as the false alarm rates, significantly increased with the presence of a light. When signal detection analysis was performed, it was further shown that participants displayed a large decrease in criterion with only a small increase in detection, similar to our results. Further illustrating the subtle nature of the detection increase, the Lovelace et al. (2003) experiment had more trials than the experiments in the current study, which is likely why the detection difference was found to be significant in their study, but only significant in our between experiments analysis and only marginally significant in the independent experiment analyses in one of our detection experiments (Experiment 3). In a second experiment, Lovelace and colleagues eliminated this response bias by blocking light-present and light-absent trials, but still found a small increase in auditory detection. Thus, while it may be that blocking the light-present and light-absent trials may have also resulted in a small increase in touch perception in our experiments, what is clear from these experiments is that there is a robust response bias for reporting an additional sensory event along with vision. This bias may be a consequence of our multisensory experiences in the real world: different sensory information when available is perfectly correlated in space and time when coming from the same object.
Visual Influences on Electrotactile Processing

Our results also help to extend the findings of two patient studies demonstrating increased tactile perception with vision (Halligan et al., 1996; Rorden et al., 1999). The patient in the Rorden et al. (1999) study only reported feeling tactile sensations when he saw his arm being touched; however, his touch detection improved (from no detection) with simultaneous presentation of a non-predictive light when it was on a rubber hand positioned over his concealed real hand. Interestingly, the patient still reported feeling some of the touches when the light was on the experimenter’s hand (32% detection), albeit to a lesser extent than when the light was on the rubber hand (51% detection). The patient also had very few false alarms during light-only trials and hardly ever reported that he felt a touch during these catch trials (4% in both conditions). Therefore, even though the visual stimulus was non-informative and flashed on every trial, the patient in the Rorden et al. study, in addition to exhibiting a change in sensitivity, may have also been revealing a response bias to report feeling more tactile stimuli when a light was present, regardless of whether the light was on the rubber hand or the experimenter’s hand.

In our study, subjects also had an increase in reported touch detection when a simultaneous, non-informative visual stimulus was presented and had very few false alarms across all experiments. Nevertheless, we found that even in experiments in which the hit rates differed significantly while the false alarm data did not, signal detection measures revealed that participants were shifting their response criteria in the presence of a visual stimulus, which at least in part accounted for the changes in reported tactile detection rates. Thus, our results highlight the need for signal detection analysis methods to be used more often in these kinds of studies.

The current results further clarify the Halligan et al. (1996) findings because we show that participants rely on the incoming visual information more than tactile information, especially when touch perception is degraded. Even though their patient claimed he could not feel any tactile stimulation unless he could see himself being touched, Halligan and colleagues demonstrated that their patient had some residual tactile sensations that were consciously unavailable but could be heightened into awareness with vision. The patient also stated that he felt his hand being touched during a video replay because he saw his impaired hand being touched and not only believed what he saw but also thought he felt a concomitant touch on his hand. Thus, in addition to any increases in touch perception, this patient also demonstrated a bias to report touch with vision of a touch-associated stimulus. In a similar way, when participants in our study reported a pulse on a Light trial, they likely believed they had felt a real touch. Ecologically, this makes sense because vision and touch are frequently associated: seeing something on one’s skin is typically accompanied by a tactile sensation.

In this study, a threshold-level tactile pulse and a flash of light were used to determine whether concurrent visual information could be used to alter touch detection. We found that a simultaneous visual event increased reports of touch in normal participants largely because of a response bias whereby participants lowered their criterion for reporting touch. A small sensitivity change was also demonstrated across the experiments. However, the change in criterion was more robust and likely contributed to an increase in reported tactile perception during both vision and touch trials as subjects were more likely to say they felt a tactile pulse when they saw a visual stimulus. Furthermore, participants also made more false alarms by reporting a touch during trials when a light was presented without a tactile pulse. These results suggest that some experimental procedures using visual cues to enhance touch perception might instead create a response bias to report tactile stimulation when a concomitant light is presented simultaneously.

4. Experimental procedures

Twenty-four undergraduate students at Rice University participated in each experiment (total of 120 subjects). All experiments were approved by the Institutional Review Board, and all participants gave their consent to be in the study. The materials and experimental design were very similar across all five experiments in this study. The participants sat in a chair with their left arms at a comfortable viewing distance on the table in front of them. Each subject’s left middle finger was prepared for the study by cleaning the finger with an electrode preparation pad (70% isopropyl alcohol and pumice) and then taping ring electrodes to the finger (Fig. 1). Participants placed their left hands on a wooden block fitted with a Velcro strap to minimize movement. A sponge was positioned underneath the participant’s forearm for comfort. Subjects had their right hands resting on their laps. Wooden planks measuring 30 cm tall and 87 cm long were erected at either end of the table to minimize visual distractions during the experiment.

Opposite the subject was a Grass-Astronest (West Warwick, Rhode Island) SD9 electrical stimulator, which delivered tactile stimulation to a subject’s finger through the ring electrodes. The electrical pulses were 0.3 ms in duration with the intensity determined by the experimenter as follows. At the beginning of the experiment, each subject’s threshold was approximated by applying electric stimulation of varying intensities to the finger, while participants reported whether or not they felt a pulse. After the experimenter determined the intensity at which approximately 50% of the stimuli were felt by each participant, a block of 10 trials was administered at this given intensity. If a subject detected between 4 and 6 stimuli out of 10, this intensity was used for the remainder of the experiment (except in Experiment 4, where an approximately 50% detection rate was used; see below). Otherwise, intensity calibrations were made, and this procedure repeated until an intensity was identified at which the subject detected between 4 and 6 stimuli out of 10. A small red LED was also taped to the ring electrodes on the participant’s left middle finger and flashed on for 5 ms when serving as the visual stimulus (Fig. 1). Tactile stimulation did not result in any movement or illumination of the LED or the participant’s finger. The computer generated a 1000-Hz tone for 200 ms to notify the subject when each trial was beginning and 500 ms after the tone had finished the visual and/or tactile stimulus was delivered. Each experiment was conducted using an Intel PC and lasted approximately 30 min.

Experiment 1 used a non-informative light simultaneously paired with a near-threshold tactile stimulus in the critical condition to determine whether it would influence touch detection. Eight practice trials followed by 80 randomly presented trials were administered (20 trials in each condition). The second
experiment examined whether pairing suprathreshold association trials before the experiment would further improve detection beyond any shifts in response criteria. Experiment 2 was identical to Experiment 1, except that subjects were given 20 association trials with suprathreshold pairings of light and touch at the beginning of the experiment. Suprathreshold tactile stimulation at the beginning of Experiment 1 was about 20% greater than threshold stimulation. In this suprathreshold pairing phase, participants were asked to report whether they saw a light, felt a touch, simultaneously saw a light and felt a touch, or saw and felt nothing. All subjects reported "both light and touch" on all of the association trials prior to commencement of Experiment 2. After the initial suprathreshold pairing phase, the tactile stimuli were returned to threshold levels by the experimenter, and the experiment followed the same format as Experiment 1 with 8 practice trials from the one actually touched and 60 experimental trials. Compared to the first two experiments, the instructions in Experiment 3 strongly emphasized reporting every tactile sensation subjects felt on their left middle fingers. These instructions were intended to induce the same bias for reporting touch across all conditions. In addition, the procedure used 8 practice trials followed by 200 trials (50 trials in each condition). This larger number of trials was used to increase the power to detect a visual enhancement of touch.

Experiment 4 was similar to Experiments 1–3, except that this experiment used a discrimination paradigm in which the visual and tactile stimuli were presented to the left index and middle fingers of each participant. Both the left middle and left index fingers were cleaned with an electrode preparation pad, and then ring electrodes were taped to both fingers. Two small red LEDs were then attached to the ring electrodes on each finger, and the electrodes were attached to separate electrical stimulators. Tactile thresholds were determined the same way as described earlier for both the index and middle fingers, except that the initial intensity was set near 60% detection. After the thresholds for both fingers were set, the experimenter then administered 20 trials (10 trials to each finger in a randomly determined order), while subjects indicated whether they felt the pulse on their index or middle finger. If a participant was correct on 5 to 7 trials, the tactile pulse was presented on the one actually touched or on the other. Compared to the first two experiments, the instructions in Experiment 3 strongly emphasized reporting every tactile sensation subjects felt on their left middle fingers. These instructions were intended to induce the same bias for reporting touch across all conditions. In addition, the procedure used 8 practice trials followed by 200 trials (50 trials in each condition). This larger number of trials was used to increase the power to detect a visual enhancement of touch.

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Current Research

Johnson and colleagues (2006) determined that subjects displayed a response bias to report touch with concomitant vision, even when electrotactile stimulation was not present. However, in these experiments, the visual and tactile stimuli were always delivered simultaneously and participants' response times were not recorded. The following set of experiments examined neurologically normal participants to determine the temporal processes associated with the previously described visuotactile interactions by recording reaction times and varying the timing between presentation of the visual and tactile stimuli. It was hypothesized that the smaller the asynchrony between vision and touch, the greater the visual influence on tactile processing.

The neural basis involved with crossmodal interactions was then established through the use of transcranial magnetic stimulation (TMS). TMS determined whether the posterior parietal cortex causally contributed to visuotactile crossmodal enhancements in the brain. Although a great deal of research has been conducted on visual and tactile processing in unimodal cortical areas as well as crossmodal processing in multimodal association cortex, few studies have looked at the specific areas of the brain concerned with and the timing sequence involved in visuotactile processing. The following TMS experiment sought to address this issue by examining the crossmodal interactions between visual and tactile processing at varying time points in different areas of the cortex. The TMS experiment used a round coil with single-pulse TMS to determine the approximate cortical location and timing sequence of processing involved with visual influences on tactile processing. It was hypothesized that TMS would disrupt normal crossmodal cortical processing in multimodal areas of the parietal cortex (but not in the
frontal control site), which would result in a decrease in the reported feelings of touch with a simultaneously presented light. Determining the location and temporal aspects involved with these visuotactile interactions could have broad implications regarding neural processing involved with vision and touch that could lead to better rehabilitative measures for patients with visual and/or tactile deficits.
Experiment 6

Visual Influences on Electrotactile Processing

This experiment was nearly identical to Experiment 1 described in Johnson et al. (2006), in which participants indicated whether they saw a light, felt a touch, perceived both simultaneously, or detected nothing. In Experiment 6, however, participants were only required to attend to the electrotactile stimulus and indicate whether or not they felt a touch, which reduced subjects’ attention to the visual stimulus and therefore possibly reduced the influence of vision on their tactile processing. In addition, subjects indicated their responses using a response box and reaction times (RT) were recorded. It was hypothesized that analyzing participants’ reaction times could help to further elucidate some of the temporal influences of vision on tactile processing.

Method

Participants. Sixteen neurologically normal subjects (7 females and 9 males) participated in this experiment after giving their informed consent. The population of subjects was drawn from the undergraduate research participation pool at Rice University and had a mean age of 19.2. All participants had normal or corrected vision and normal touch perception. This experiment was approved by the Institutional Review Board at Rice University.

Materials. Experiment 6 used a detection paradigm in which the visual and electrotactile stimuli were presented to the middle finger on the left or right hand of each participant (Figure 1). The previously described experiments only tested the left hands of subjects. During the experiment, participants sat in a chair with their left and right arms at a comfortable viewing distance on the table in front of them. Half of the subjects were
Figure 1. The apparatus and stimuli used in this study are shown. Electrotactile stimulation was delivered through ring electrodes, while visual stimulation was presented with a small red LED.
tested with their left hand, whereas the other half with their right hand. The middle finger
of the hand being tested was cleaned with an electrode preparation pad (70% isopropyl
alcohol and pumice) and then ring electrodes were taped to that finger (Figure 1).

A Grass-Astromed (West Warwick, Rhode Island) SD9 electrical stimulator was
located opposite the subject to deliver tactile stimulation to a subject’s fingers through the
ring electrodes. The electrical pulse was 0.3 ms in duration with the intensity determined
by the experimenter as follows. At the beginning of the experiment, each subject’s
threshold was approximated by applying electric stimulation of varying intensities to the
middle finger while a participant reported whether or not he or she had felt the pulse.
After the experimenter determined the intensity at which approximately 50% of the
electrotactile stimuli were felt on a participant’s middle finger, the experimenter then
administered 10 tactile pulses while subjects indicated whether they felt the touch on
their middle finger or not. If a participant reported feeling 4 to 6 of the 10 given
electrotactile pulses, this intensity was used for the remainder of the experiment.
Otherwise, intensity calibrations were made and this procedure repeated until an intensity
was found at which the participant reported feeling 4 to 6 of the 10 electrotactile pulses.
A small red LED was also taped to the ring electrodes on the participant’s middle finger
and flashed on for 5 ms when serving as the visual stimulus (Figure 1). Electrical
stimulation did not result in any movement of the LED or participant’s fingers, nor did
the presentation of the LED result in any reported tactile sensations on participants’
fingers. The computer generated a 1000 Hz tone for 250 ms to notify the subject when
each trial would begin and 500 ms after the tone had finished the stimuli were delivered.
The experiment was conducted using an Intel PC running E-Prime software (PST, Pittsburgh) and lasted approximately 30 minutes.

**Experimental Design.** The experiment had four conditions: 1) Light trials where visual stimulation was presented via the LED; 2) Touch trials where subjects were given electrotactile stimulation via the ring electrodes; 3) Both trials where visual and tactile stimuli were delivered simultaneously; and 4) Catch trials where no sensory stimulation was delivered to the subject. The participant’s task was to decide whether or not they felt the electrotactile stimulation on each trial. Subjects used the hand not being stimulated to respond either “yes” or “no” with a button press on each trial and reaction times were recorded. Touch detection percentages were calculated based on the number of “yes” responses participants reported for each condition. False alarms occurred when subjects stated they felt a pulse on Light or Catch trials where no electrotactile stimulation had been delivered to the participant. Participants were asked to look at the hand being stimulated so they could see the light flash, but were not required to report any visual information. The instructions emphasized reporting every tactile sensation subjects felt on their stimulated finger as quickly and accurately as possible. If a participant did not respond within 2500 ms after stimulus presentation, the computer program automatically advanced to the next trial and that trial was then excluded from analyses. In Experiment 6, each of the four conditions had 40 trials, for a total of 160 trials.

**Results**

Before the data in Experiment 6 was analyzed, it was transformed by removing reaction time outliers that were more than 3 standard deviations above or below the mean.
for each condition in each of the 16 subjects. This transformation resulted in the removal of 1.8% of the total number of data trials.

*Detection Analyses.* A 2 x 4 mixed-factor ANOVA was conducted on the reported touch detection data with hand laterality (left and right) as the between-subject factor and condition (Both, Touch, Light, and Catch) as the within-subject factor. A main effect of condition was found \(F(3,42) = 48.837, p < .001\). However, the laterality difference in detection between the left and right hands was not significant \(F(1,14) = .658, p = .431\). The interaction between condition and hand laterality was also not significant \(F(3,42) = .154, p = .927\); therefore, the factor of tested hand was collapsed across in further detection analyses. Overall, the reported touch detection percentages across the four conditions were significantly different from each other \(F(3, 45) = 51.758, p < .001\). Reported touch detection averages can be seen in Figure 2. Tactile detection percentages increased 5.3% during Both light and touch trials compared to Touch trials.

In Experiment 6, participants reported that they felt the electrotactile pulse significantly more often when it was paired with the visual stimulus in Both trials than when it was presented alone in Touch trials \(t(15) = 2.505, p = .024, \text{ two-tailed}\). Subjects also reported feeling the electrotactile pulse on Light trials significantly more often than they did on Catch trials \(t(15) = 2.208, p = .043, \text{ two-tailed}\). This 4.7% increase in false alarms indicated that the presence of the visual stimulus led subjects to report electrotactile stimulation significantly more often even when a pulse was not presented. It also appears that this false alarm increase was the primary contributor to the 5.3% increase in touch detection during Both light and touch trials compared to Touch trials.
Figure 2. The detection results from Experiment 6 are shown. The detection difference between Both and Touch trials is significant, as is the false alarm difference between Light and Catch trials ($p's < .05$).
Reaction Time Analyses. A 2 x 4 mixed-factor ANOVA was conducted on the RT data with hand laterality (left and right) as the between-subject factor and condition (Both, Touch, Light, and Catch) as the within-subject factor. A main effect of condition was found ($F(3,42) = 4.196, p = .011$). The laterality difference in reaction times between the left and right hands was also significant ($F(1,14) = 11.300, p = .005$). On average, participants who responded with their left hands were 164 ms faster than those responding with their right hands. However, this pattern was the same across all four conditions and the interaction between condition and hand laterality was not significant ($F(3,42) = .506, p = .680$); therefore, the factor of tested hand was collapsed across in further RT analyses. Overall, the RTs across the four conditions were significantly different from each other ($F(3, 45) = 4.339, p = .009$). Reaction time averages for each condition can be seen in Figure 3. Overall, trials in which a stimulus was presented were easier to detect and subjects responded more quickly on those trials. Furthermore, participants were significantly faster when responding to Both visual and tactile trials compared to Touch or Catch trials ($t(15) = 2.431, p = .028$, two-tailed and $t(15) = 2.632, p = .019$, two-tailed, respectively). The RT difference between Both vision and touch trials and the Light trials was not significantly different ($t(15) = 1.740, p = .102$, two-tailed), even though subjects responded more slowly on the Light trials.

Signal Detection Analysis. Signal detection analyses were used to calculate $d'$ and $c$ values in a similar procedure as those described in (Johnson et al., 2006). Changes in sensitivity were measured using $d'$, $[d' = z(\text{Hits}) - z(\text{False alarms})]$, while changes in criterion, a measure of response bias, were measured using $c$, $[c = -z(\text{Hits}) + z(\text{False alarms})]/2)$, (Macmillan & Creelman, 1991). For those participants who did not commit
Figure 3. The RT results from Experiment 6 are shown. The RT for the Both light and touch trials is significantly less than the Touch and Catch trials ($p$'s < .05).
a false alarm, false alarm rates were approximated to allow for signal detection analyses by dividing 0.5 by the number of trials in the condition (Stanislaw & Todorov, 1999). Signal detection averages for Experiment 6 are shown in Figure 4.

A 2 x 2 mixed-factor ANOVA was conducted on the d’ data with hand laterality (left and right) as the between-subject factor and sensitivity (Both and Touch d’ values) as the within-subject factor. There was no difference between the Both and Touch d’ values and a main effect of sensitivity was not found ($F(1,14) = .175, p = .682$). The main effect of laterality was also not significant ($F(1,14) = .178, p = .680$). Furthermore, the interaction between sensitivity and laterality was not significant ($F(1,14) = .006, p = .940$). After collapsing across the factor of hand laterality, the difference between sensitivity in Both vision and touch trials compared to Touch trials was not significant ($t(15) = .433, p = .671$). Sensitivity averages are shown in Figure 4.

A 2 x 2 mixed-factor ANOVA was conducted on the criterion shift data with hand laterality (left and right) as the between-subject factor and response bias (Both and Touch c values) as the within-subject factor. A main effect of response bias was found ($F(1,14) = 7.695, p = .015$). However, the main effect of laterality was not significant ($F(1,14) = 1.474, p = .245$) and neither was the interaction between response bias and laterality ($F(1,14) = .143, p = .711$). After collapsing across laterality, the difference in response bias between Both light and touch trials compared to Touch trials was significant ($t(15) = 2.857, p = .012$, two-tailed). The visual stimulus had an effect on participants’ response biases and subjects lowered their criterions during light-present trials and reported more tactile pulses compared to light-absent trials. Response bias averages are shown in Figure 4.
**Figure 4.** The sensitivity and response bias data for Experiment 6 are shown. The sensitivity difference is not significant, but the response bias difference is significant ($p < .05$).
Discussion

Experiment 6 demonstrated a 5.3% increase in reported touch perception during both vision and touch trials when the visual stimulus was present compared to touch trials where it was absent. This difference in tactile perception was not as great as those described in Experiments 1-5, which had enhancements ranging from 6.9% to 15.6% (Johnson et al., 2006). However, in this experiment, participants were only required to respond to the electrotactile stimulus and not the visual stimulus. Therefore, the somewhat muted tactile enhancement in this experiment was likely due to the fact that subjects were not paying attention to the light. The experiment was deliberately designed this way to look at how vision influences tactile processing, even when the visual stimulus is irrelevant and does not require a response from subjects. Johnson et al. (2006) previously demonstrated that the increase in touch detection during both light and touch trials was mostly due to a response bias where subjects lowered their criteria for detecting an electrotactile stimulus with simultaneous presentation of a visual stimulus; however, a small increase in sensitivity was found across Experiments 1-3. In this experiment, the results indicated that the detection increase between the both and touch trials (5.3%) was nearly identical to the false alarm increase between Light and Catch trials (4.7%). In Experiment 6, it could be that when participants were not required to pay attention to the light, the increase in reported touch during trials where the visual stimulus was presented was entirely due to a criterion shift. The signal detection analyses confirmed that subjects exhibited a significant response bias. Participants were more likely to report feeling a touch when a visual stimulus was delivered, even if the electrotactile stimulus was not presented. The difference in sensitivity between the both
and Touch trials was not significant and not even in the predicted direction. The absence of even a small effect of sensitivity in Experiment 6 was likely due to the fact that the visual stimulus was irrelevant and did not require a response. The RT data in this experiment indicated that subjects responded more quickly when a stimulus was present on a trial. Furthermore, subjects responded significantly faster on light-present trials (Both and Light trials) compared to light-absent trials (Touch and Catch trials).
Experiment 7

Visual Influences on Electrotactile Processing at Various SOAs

This experiment assessed the time course associated with the effects of the visuotactile interactions reported in Experiments 1-6 and was very similar to the previously described experiments. However, Experiment 7 had several different stimulus onset asynchronies (SOAs) between the visual and tactile events during the Both light and touch trials. It was hypothesized that only synchronous or very close in time visual and tactile stimuli would induce visual enhancing effects on touch. This time window could be related to the temporal resolutions of vision and touch. If so, then we predicted that a visual stimulus would only enhance touch perception if the visual information was presented simultaneously or within a very short time before or after the electrotactile stimulus.

Method

Participants. Sixteen neurologically normal subjects (7 females and 9 males) participated in Experiment 7 after giving their informed consent. The population of subjects was drawn from the undergraduate research participation pool at Rice University and had a mean age of 20.0. All participants had normal or corrected vision and normal touch perception. This experiment was approved by the Institutional Review Board at Rice University.

Materials. The experimental setup and paradigm was very similar to the previously described experiments. Visual and electrotactile stimuli were again presented to the middle finger on the left or right hand of each participant. Half of the subjects were tested with the left hand, whereas the other half with their right hand. After the
experimenter determined the intensity at which approximately 50% of the tactile pulses were felt on a participant’s middle finger, a small red LED was then taped to the exterior of the ring electrodes on the participant’s middle finger and flashed on for 5 ms when serving as the visual stimulus (Figure 1). The experiment lasted approximately 45 minutes.

**Experimental Design.** Experiment 7 had twelve randomly presented conditions: 1) Light trials, 2) Touch trials, 3-11) Both light and touch trials with nine different SOAs, and 12) Catch trials where no sensory stimulation was delivered. In a detection design similar to Experiment 6, participants indicated whether they had felt an electrotactile pulse during each trial and reaction times were recorded using a response box. Subjects were asked to look at the hand being stimulated so they could see the visual stimulus, but were not required to report any visual information. Nine SOAs (ranging from -100 to +100 ms asynchronies with 25 ms increments) between vision and touch were used in the Both conditions. In Experiment 7, each of the twelve conditions had 40 trials, for a total of 480 trials.

**Results**

Before the data in Experiment 7 was analyzed, it was transformed by removing reaction time outliers that were more than 3 standard deviations above or below the mean for each condition in each of the 16 subjects. This transformation resulted in the removal of 2.7% of the total number of data trials.

**Detection Analyses.** A 2 x 12 mixed-factor ANOVA was conducted on the reported touch detection data with hand laterality (left and right) as the between-subject factor and condition (9 Both conditions with different SOAs, Touch, Light, and Catch.
trials) as the within-subject factor. A main effect of condition was found ($F(11,154) = 45.302, p < .001$). However, the laterality difference in detection between the left and right hands was not significant ($F(1,14) = .051, p = .825$). The interaction between condition and hand laterality was also not significant ($F(11,154) = .713, p = .725$); therefore, the factor of tested hand was collapsed across in further detection analyses. As shown in Figure 5, reported tactile percentages across the 12 conditions were significantly different from each other ($F(11,165) = 46.186, p < .001$). Touch detection increased in a range from 6.1% to 16.0% during Both trials with various SOAs between the visual and tactile stimuli compared to Touch trials (Figure 6). When comparing only the 9 Both conditions with different SOAs, the conditions were significantly different from each other ($F(8,120) = 3.325, p = .002$). Furthermore, the smaller the asynchrony between the visual and tactile stimuli, the larger the percent difference between the Both conditions and the Touch condition. This effect resulted in a significant quadratic trend ($F(1,15) = 22.707, p < .001$). As shown in Figure 6, Both light and touch trials with SOAs ranging from -50 ms (visual stimulus appearing 50 ms before the electrotactile stimulus) to +75 ms (visual stimulus appearing 75 ms after the tactile pulse) are all significantly greater than the Touch condition (all $r’s > 4.0$ and all $p’s < .005$, Bonferroni correction for multiple comparisons).

**Reaction Time Analyses.** A 2 x 12 mixed-factor ANOVA was conducted on the reaction time data with hand laterality (left and right) as the between-subject factor and condition (9 Both conditions with various SOAs, Touch, Light, and Catch trials) as the within-subject factor. A main effect of condition was found ($F(11,154) = 21.392, p < .001$). However, the laterality difference in reaction time between the left and right hands
Figure 5. The detection results for Experiment 7 are shown. A significant quadratic trend was found for the Both light and touch trials ($p < .05$), which demonstrated that as the asynchrony between vision and touch decreased tactile detection increased.
Figure 6. The difference results for Experiment 7 are shown. Black columns indicate differences where the Both condition was significantly greater than the Touch condition ($p's < .005$), whereas grey columns indicate non-significant differences between conditions (when adjusted for multiple comparisons).
was not significant ($F(1,14) = .194, p = .666$). The interaction between condition and hand laterality was also not significant ($F(11,154) = 1.510, p = .133$); therefore, the factor of tested hand was collapsed across in further reaction time analyses. Overall, the RTs across the 12 conditions were significantly different from each other ($F(11,165) = 20.688, p < .001$). When comparing the RTs from just the 9 Both conditions with different SOAs, the conditions were significantly different from each other ($F(8,120) = 23.407, p < .001$). As shown in Figure 7, participants responded faster when the visual stimulus arrived before the electrotactile stimulus and slower when the light arrived after the tactile pulse. In the Both light and touch conditions, the RT data increased linearly across the various asynchronies from -100 ms to +100 ms, which resulted in a significant linear trend ($F(1,15) = 101.014, p < .001$). This linear trend demonstrated that subjects were most likely waiting for the light to appear during the visual and tactile trials before they responded whether or not they had felt the touch, even though participants were not required to respond to the visual stimulus. Interestingly, on trials where the visual stimulus preceded the electrotactile stimulus by 50 – 100 ms, subjects were significantly faster at responding on those Both vision and touch trials compared to the Light, Touch, and Catch trials (all $p$’s < .004, Bonferroni correction for multiple comparisons) (Figure 7).

**Signal Detection Analyses.** A 2 x 10 mixed-factor ANOVA was conducted on the sensitivity data with hand laterality (left and right) as the between-subject factor and condition (9 Both conditions with different SOAs and the Touch condition) as the within-subject factor. A main effect of condition was found ($F(9,126) = 2.121, p = .032$). However, the laterality difference for sensitivity between the left and right hands was not
Figure 7. The RT results for Experiment 7 are shown. When the visual stimulus arrived 50 - 100 ms before the electrotactile stimulus, participants’ RTs were significantly faster compared to Light, Touch, and Catch trials (p’s < .005, adjusted for multiple comparisons).
significant \( (F(1,14) = .302, p = .591) \). The interaction between condition and hand laterality was also not significant \( (F(9,126) = .546, p = .838) \); therefore, the factor of tested hand was collapsed across in further sensitivity analyses. Overall, the \( d' \) values across the 10 conditions were significantly different from each other \( (F(9,135) = 2.187, p = .027) \). When comparing only the 9 Both conditions with different SOAs, the sensitivity values were significantly different from each other \( (F(8,120) = 3.423, p = .001) \).

Participants also had greater reported \( d' \) values on trials in which the asynchrony between vision and touch was small (Figure 8). Furthermore, as the separation between the presentation of the visual and tactile stimuli increased, subjects’ \( d' \) values decreased. This quadratic trend was significant \( (F(1,15) = 21.149, p < .001) \). As shown in Figure 8, however, none of the Both \( d' \) conditions were significantly different from the Touch \( d' \) condition (all \( p's > .250 \), Bonferroni correction for multiple comparisons).

A 2 x 10 mixed-factor ANOVA was conducted on the response bias data with hand laterality (left and right) as the between-subject factor and condition (9 Both conditions with different SOAs and the Touch condition) as the within-subject factor. A main effect of condition was found \( (F(9,126) = 9.565, p < .001) \). The laterality difference between the left and right hands was not significant \( (F(1,14) = .726, p = .409) \). The interaction between condition and hand laterality was also not significant \( (F(9,126) = 1.189, p = .308) \); therefore, the factor of tested hand was collapsed across in further response bias analyses. Overall, the \( c \) values across the 10 conditions were significantly different from each other \( (F(9,135) = 9.447, p < .001) \). When comparing the 9 Both conditions with various SOAs, the criterion values were significantly different from each other \( (F(8,120) = 3.423, p = .001) \). Furthermore, as the separation between vision and
Figure 8. Signal detection results are shown for Experiment 7. While the sensitivity and response bias data both displayed significant quadratic trends (p’s < .001), only the c values were significantly lowered in the Both light and touch conditions compared to the Touch condition (p’s < .005).
touch decreased, participants adopted a more liberal response bias so that the difference between the Both and Touch criterion values were greater the shorter the SOA between the visual and tactile stimuli. This effect resulted in a significant quadratic trend ($F(1,15) = 21.149, p < .001$), which demonstrated that subjects were shifting their response criteria as the asynchrony between the visual and tactile stimuli increased. In addition, as shown in Figure 8, the $c$ values in the Both conditions were all significantly less than the Touch $c$ value (all $p$'s < .005, Bonferroni correction for multiple comparisons). The signal detection analyses in Experiment 7 mimicked those described in Johnson et al. (2006), indicating that the tactile enhancement shown during Both vision and touch trials was due to a response bias where participants' were more likely to report feeling a touch when the visual stimulus was presented in close proximity to the electrotactile stimulus.

Discussion

Interestingly, this experiment had 9 Both light and touch conditions and therefore the visual stimulus was somewhat predictive of the tactile pulse, which resulted in an increase in reported feelings of touch during trials where the visual stimulus was presented with the electrotactile stimulus. The percent increases during Both light and touch trials ranged from 6.1% to 16.0% (Figure 6). Experiment 7 found that subjects’ Both vision and touch data displayed a significant quadratic trend so that the smaller the temporal asynchrony between the visual and tactile stimuli, the greater the increase in reported touch overall. When tested individually, detection rates for the Both light and touch trials with SOAs ranging from -50 ms to +75 ms were significantly greater than the Touch trials. While some of the differences in detection between Touch trials and Both trials with greater asynchronies between vision and touch were not significant, criterion
shifts for all Both light and touch conditions were significantly lower than the Touch condition. Furthermore, Experiment 7 also displayed a significant quadratic trend for the response bias data, which demonstrated that the smaller the asynchrony between the visual and tactile stimuli, the greater the decrease in subjects’ response criteria. The response bias data therefore explained why participants reported more tactile pulses on Both vision and touch trials with shorter SOAs overall. The sensitivity data also displayed a significant quadratic trend where subjects’ $d'$ values were greater the smaller the asynchrony between vision and touch. However, none of the Both light and touch sensitivity values were significantly different from the Touch $d'$ value, which mimicked the results found in Experiment 6. The RT results in Experiment 7 were also similar to Experiment 6 and participants responded faster on trials where a light was presented. Furthermore, the earlier the light was presented on a Both trial, the faster the subjects responded to the tactile pulse, which resulted in a significant linear trend. The linear trend for Both vision and touch trials indicated that participants were waiting for the light to be delivered before they responded whether or not they had felt a touch. In addition, Both light and touch trials where the visual stimulus was delivered 50 ms or more before the tactile pulse were significantly faster than the Light, Touch, and Catch trials. As shown in Figure 6, however, faster reaction times did not necessarily result in greater touch detection. The presence of the visual stimulus determined when subjects would respond, but was not predictive of how they would respond to the electrotactile stimulus. Overall, Experiment 7 was very important in determining the time course associated with the reported increase in touch detection during light-present trials.
Experiment 8

The Perception of Simultaneity between Vision and Touch

Similar to Experiment 7, this experiment sought to expand the understanding of the temporal processes involved with visual and tactile interactions in the brain. To this effort, Experiment 8 explored the perception of simultaneity between visual and tactile stimuli using temporal order judgments (TOJ). In this experiment, the same SOAs as those in Experiment 7 were used between vision and touch. However, participants were asked to determine which modality (vision or touch) they had experienced first. Previous research has demonstrated that an attentional bias exists towards the visual modality when subjects were asked to determine which sensory modality occurred first (Spence, Shore, & Klein, 2001). Further research has also shown that participants found multisensory TOJs more difficult when sensory modalities shared the same spatial information (Spence, Baddeley, Zampini, James, & Shore, 2003). This experiment was therefore conducted to replicate these findings using the experimental paradigm described in Experiment 7 and to determine the temporal processes involved with the visuotactile interactions described previously. It was hypothesized that participants would be able to distinguish which sensory modality had arrived first at larger SOAs and therefore these longer SOAs conditions would also have faster reaction times.

Method

Participants. Sixteen neurologically normal subjects participated in this experiment (11 females and 5 males). The mean age of the subjects in this experiment was 19.0 years old, as the population was drawn from the undergraduate research participation pool at Rice University. All participants had normal or corrected vision and
normal touch perception. This experiment was approved by the Institutional Review Board at Rice University.

*Materials.* This experimental setup and paradigm were similar to the previously described experiments. Visual and tactile stimuli were again presented to the middle finger on the left or right hand of each participant. Half of the subjects were tested with their left hands, whereas the other half with their right hands. After the experimenter determined the lowest intensity at which approximately all of the electrotactile stimuli were felt on a participant’s middle finger, a small red LED was then taped to the ring electrodes on the participant’s middle finger and flashed on for 5 ms when serving as the visual stimulus (Figure 1). Experiment 8 lasted approximately 45 minutes.

*Experimental Design.* Based on the previous experiment, Experiment 8 had eight SOAs between the presentation of the visual and electrotactile stimuli (-100, -75, -50, -25, 25, 50, 75, and 100 ms asynchronies). The participant’s task was to decide which stimulus modality was delivered first on each trial. Using the hand not being electrically stimulated, subjects responded either “light” or “touch” with a button press on each trial and reaction times were recorded. If subjects did not feel a pulse on a given trial or were unsure which modality they detected first, they were instructed to make a guess regarding which modality was delivered first. Light detection percentages were calculated based on the number of “light first” responses participants reported for each condition. Each of the eight SOAs had 50 trials, for a total of 400 trials in Experiment 8.

*Results*

Before the data in Experiment 8 was analyzed, it was transformed by removing reaction time outliers that were more than 3 standard deviations above or below the mean
for each condition in each of the 16 subjects. This transformation resulted in the removal of 2.4% of the total number of data trials.

Detection Analyses. A 2 x 8 mixed-factor ANOVA was conducted on the reported light detection data with the between-subject factor of hand laterality (left and right) and the within-subject factor of SOA condition (-100, -75, -50, -25, 25, 50, 75, and 100 ms asynchronies). A main effect of condition was found \((F(7,98) = 10.786, p < .001)\). The interaction between SOA condition and hand laterality was also significant \((F(7,98) = 2.223, p = .039)\). Nevertheless, the factor of hand laterality was collapsed across in further detection analyses due to the fact that a main effect of laterality was not found between the left and right hands \((F(1,14) = .384, p = .545)\). Overall, reported light detection percentages across the 8 SOA conditions were significantly different from one another \((F(7,105) = 9.973, p < .001)\). Furthermore, as the SOA increased between the visual and tactile stimuli, subjects were more likely to correctly identify the modality that had arrived first. As shown in Figure 9, this effect resulted in a significant linear trend \((F(1,15) = 16.253, p = .001)\). Nevertheless, only the conditions where the visual stimulus preceded the electrotactile stimulus were significantly different than chance (50% detection) when compared individually (all \(t's > 2.1\) and \(p's < .05\)). When the light arrived after the touch, subjects were no better than chance at detecting which stimulus had been presented first (all \(t's < 1.6\) and \(p's > .13\)).

Reaction Time Analyses. A 2 x 8 mixed-factor ANOVA was conducted on the TOJ reaction time data with the between-subject factor of hand laterality (left and right) and the within-subject factor of SOA condition (-100, -75, -50, -25, 25, 50, 75, and 100 ms asynchronies). A main effect of condition was not found \((F(7,98) = .769, p = .615)\).
Figure 9. Experiment 8 detection results are shown. When the visual stimulus arrived before the electrotactile stimulus, participants were significantly better than chance at reporting that they saw the light first ($p$'s < .05); however, when the tactile pulse arrived prior to the light, subjects were no better than chance at determining which modality had arrived first ($p$'s > .05).
The laterality difference in reaction times between the left and right hands was not significant \((F(1,14) = 1.115, p = .309)\). The interaction between SOA condition and hand laterality was also not significant \((F(7,98) = .751, p = .630)\); therefore, the factor of tested hand was collapsed across in further reaction time analyses. Overall, the RTs across the 8 conditions were not significantly different from each other \((F(7,105) = .782, p = .604)\). As shown in Figure 10, participants’ RTs were very similar even at larger SOAs between the visual and tactile stimuli. This effect demonstrated that participants were likely waiting for both stimuli to be delivered before they responded which had arrived first, which accounts for why subjects’ RTs did not vary across the various SOAs. This cognitive effect of waiting also likely resulted in the elevated RTs seen in Experiment 8 (Figure 10).

**Discussion**

Experiment 8 explored the perception of simultaneity between visual and tactile stimuli using temporal order judgments (TOJ). In this experiment, when the visual stimulus came before the electrotactile stimulus, participants reported that the light appeared first significantly more often than chance. However, when the tactile pulse preceded the visual stimulus, subjects did not detect which modality arrived first and were no better than chance. Even when the touch was delivered 100 ms prior to the light, subjects were still no better than chance at reporting that the electrotactile stimulus had arrived first. These results suggest that it is more difficult for participants to determine \textit{when} an electrotactile stimulus was delivered than to simply report \textit{if} a touch has occurred as in previous experiments. Perhaps subjects did not feel the tactile pulse on every trial like they were supposed to, which is why it was easier for them to report the
Figure 10. The RT data for Experiment 8 is shown. Participants’ RTs did not significantly differ between conditions as it appeared subjects were waiting for both modalities to arrive before deciding which one was delivered first.
light compared to the touch. Furthermore, we had predicted faster RTs at longer SOA discrepancies and slower RTs at shorter SOAs due to the increased difficulty in determining which sensory modality had arrived first, but the reaction time results indicated that participants' response times were consistent across all conditions. However, subjects' RTs were considerably slower in Experiment 8 compared to Experiments 6 and 7. Perhaps participants still had trouble determining which modality had arrived first even at the longer SOAs, which resulted in greater RTs across all the conditions. Further research needs to be conducted to determine the discrepancies described in Experiment 8.
Experiment 9

TMS Experiment Determining Crossmodal Interactions of Vision and Touch

Transcranial magnetic stimulation (TMS) was used to transiently disrupt neural functioning and thus elucidate the cortical location and temporal sequence associated with visuotactile interactions. This TMS experiment provided a follow up to the experiments described in Johnson et al. (2006) and Experiments 6-8 described above using a simultaneous visual stimulus with an electrotactile pulse. This single-pulse TMS experiment was conducted using a round coil to approximate the cortical location and temporal sequence associated with the crossmodal processing. TMS is a non-invasive technique that stimulates the cortex with brief magnetic pulses, which induce electrical currents in the brain and briefly interrupt normal cortical processing (Hallett, 2000; Jahanshahi & Rothwell, 2000; Pascual-Leone, Walsh, & Rothwell, 2000). TMS can therefore determine if a given cortical region is necessary for a given cognitive process, unlike other neuroimaging techniques which rely on correlational data (fMRI, PET, EEG). In addition to establishing causal relationships, TMS also has a relatively high temporal resolution, which makes this technique ideal to look at sequencing crossmodal interactions in the cortex.

Method

Participants. Eight neurologically normal subjects participated in this experiment (2 males and 6 females). The mean age of the subjects in this experiment was 24.9 years old, as the population was drawn from the academic community at Rice University. This study was approved by the Institutional Review Board at Rice University. Informed consent was obtained from all participants, who were advised of the experiment’s
purpose and procedures, as well as risks and benefits. Participants were compensated $10/hour for their time. All subjects had normal or corrected vision and normal touch perception. Also, participants did not have any metal objects in their head or neck area, nor did they have any implants, such as a pacemaker. Furthermore, only subjects who had no history of neurological and/or psychiatric disorders were allowed to participate in this TMS study.

Experimental Design. The TMS experiment was designed to determine approximate cortical locations and temporal sequences involved with visual and tactile processing. The experimental paradigm was similar to Experiment 6 described previously and used a visual stimulus and/or tactile pulse on a participant's middle finger of his/her left or right hand. Experiment 9 had four randomly presented types of trials: 1) Light trials; 2) Touch trials; 3) Both light and touch trials; and 4) Catch trials where sensory stimulation was not delivered to the subject. Using the hand not receiving electrotactile stimulation, participants indicated if they felt the tactile pulse and reaction times were recorded on each trial using a response box. In Experiment 9, subjects had either their left or right hemispheres tested using TMS, which was counterbalanced across participants. Two different TMS SOAs (100 and 200 ms) were tested, as well as a no TMS condition. Participants received magnetic stimulation counterbalanced across two different cortical sites (posterior parietal cortex and frontal cortex).

The experiment tested two different cortical sites: the posterior parietal cortex and the frontal cortex. While the frontal cortex was stimulated as a control site, the posterior parietal cortex was stimulated because previous research had demonstrated that visual and tactile crossmodal processes interacted in that region (Andersen et al., 1997; Colby &
The experiment had 20 trials in each of the four experimental conditions across the three different TMS SOAs for a total of 240 trials at each stimulation site (480 trials total).

**Transcranial Magnetic Stimulation.** In this experiment, a Cadwell Laboratories MES-10 stimulator (Kennewick, WA) was used, which created a 2.2 Tesla field at maximum intensity and a shape determined by the configuration of the coil (Cadwell, 1990). The hand area of the motor cortex was located in each participant using a focal figure-eight TMS coil (each component measuring 4.5 cm). The hand area of the motor cortex was identified as the region capable of generating noticeable movements in any of the muscles in the contralateral hand. In Experiment 9, a larger 9 cm circular coil was used after the motor hand area had been localized with the figure-eight coil. For each participant, the minimum motor threshold intensity was determined with the round coil over the hand motor area and then an intensity 10% above this motor threshold was used over the subject’s parietal and frontal cortices. The TMS pulse was triggered from the computer through the parallel port and was time-locked to the presentation of the visual and/or electrotactile stimuli. The cortical TMS sites were determined in the following way. The anterior edge of the TMS coil was positioned 3 cm posterior and 2 cm lateral to the hand area in the posterior parietal block. During the frontal control block, the posterior edge of the coil was positioned 3 cm anterior to the hand area.

**Results**

Before the TMS experiment data was analyzed, it was transformed by removing reaction time outliers that were more than 3 standard deviations above or below the mean for each condition in each of the 8 subjects. This transformation resulted in the removal
of 2.1% of the total number of data trials. The purpose of this data trimming was that occasionally the TMS coil would become overheated during a block of trials and had to be changed out for an alternate coil before subjects had a chance to respond, which resulted in a very long reaction time. Occasionally on other trials, the participant would forget to respond “yes” or “no” immediately after stimuli presentation, and would simply make a guess several seconds later so that the experiment would advance to the next trial. Previous experiments had dealt with this problem by automatically advancing to the next trial if the participant had not responded after 2500 ms and the trial was then excluded. This experiment had to be designed differently, however, because the experimenter knew the TMS coils occasionally overheated and did not want the computer program to automatically advance through the trials while the TMS coil was being changed. Therefore, the program in Experiment 9 waited for the participant to respond before continuing to the next trial, which resulted in occasional RT outliers that needed to be removed.

Detection. A 2 x 2 x 4 x 3 mixed-factor ANOVA was first conducted on the reported touch detection data to determine if any laterality effects occurred between the left and right hands and/or hemispheres. The four factors were the between-subject factor of tested hand/hemisphere (left and right) and the within-subject factors of TMS site (parietal and frontal), condition (Both, Touch, Light, and Catch), and SOA (100 ms, 200 ms, and no TMS trials). The main effect of hand/hemisphere was not significant ($F(1,6) = .184, p = .683$). Furthermore, none of the interactions involving the factor of hand/hemisphere were significant (all $F$'s $< 1.75$, all $p$'s $> 0.2$). Therefore, the factor of hand/hemisphere was collapsed across in all further analyses.
A 2 x 4 x 3 mixed-factor ANOVA was conducted on the reported touch detection data with the within-subject factors of TMS site (parietal and frontal), condition (Both, Touch, Light, and Catch), and SOA (100 ms, 200 ms, and no TMS trials). As shown in Figure 11 (A and B), the tactile detection percentages across the 4 conditions were significantly different from one another \((F(3,21) = 19.557, p < .001)\). The main effect of SOA was also significant \((F(2,14) = 4.480, p = .031)\) and subjects reported feeling more touches not only on trials where the tactile pulse was present, but also on trials where the electrotactile stimulus was not present (false alarms). The interaction between condition and SOA was also significant \((F(6,42) = 2.512, p = .036)\). However, the main effect of TMS location was not significant \((F(1,7) = .008, p = .931)\). The TMS interactions with condition and SOA were also not significant \((F(3,21) = .639, p = .598\) and \(F(2,14) = .177, p = .840\), respectively). Finally, the interaction between TMS, condition, and SOA was not significant \((F(6,42) = .782, p = .589)\).

A comparison between the touch-present trials (Both and Touch conditions) was made to determine the effect of the visual stimulus on detecting the electrotactile stimulus. A 2 x 2 x 3 mixed-factor ANOVA was conducted on the touch detection data with the within-subject factors of TMS site (parietal and frontal), condition (Both and Touch trials), and SOA (100 ms, 200 ms, and no TMS trials). Overall, subjects reported feeling the electrotactile stimulus more often when a light was present on the Both light and touch trials compared to the Touch trials, which resulted in a main effect of condition \((F(1,7) = 10.089, p = .016)\). The main effect of SOA was significant \((F(2,14) = 4.368, p = .034)\), while the interaction between condition and SOA approached significance \((F(2,14) = 3.454, p = .060)\). However, the main effect of TMS location was not
Figure 11. (A) The detection results for the frontal TMS condition in Experiment 9 are shown. (B) The detection results for the parietal TMS condition are shown.
significant \( F(1,7) = .102, p = .759 \). The TMS interactions with condition and SOA were also not significant \( F(1,7) = .941, p = .364 \) and \( F(2,14) = .186, p = .832 \), respectively. Finally, the interaction between TMS, condition, and SOA was not significant \( F(2,14) = 1.097, p = .361 \).

Individual comparisons between specific conditions were also made. At the frontal TMS site, participants reported feeling 4.9% more touches on Both light and touch trials compared to the Touch trials when TMS was not delivered, but this difference was not significant \( t(7) = .900, p = .398 \). The 1.6% and -1.4% differences between the Both and Touch trials when TMS was delivered 100 and 200 ms (respectively) after the stimuli over the frontal cortex were also not significantly different (100 ms: \( t(7) = .313, p = .763 \); 200 ms: \( t(7) = .290, p = .780 \)). At the parietal TMS site, participants reported feeling 15.1% more touches during the Both vision and touch trials compared to the Touch trials when TMS was not delivered, and this difference was significant \( t(7) = 3.01, p = .020 \). For unforeseen reasons, the differences between the baseline (no TMS) frontal and parietal conditions appear different from one another. However, the two no TMS Both conditions and the two no TMS Touch conditions are not significantly different from one another (Both: \( t(7) = .958, p = .370 \); Touch: \( t(7) = 1.086, p = .314 \), respectively). Furthermore, when comparing the 4.9% increase during Both light and touch trials in the frontal no TMS condition to the 15.1% increase during Both vision and touch trials in the parietal no TMS condition, the differences were also not significant \( t(7) = 1.226, p = .260 \). In addition, the -3.3% and 7.5% differences between the Both and Touch trials (respectively) when TMS was delivered 100 and 200 ms after
the stimuli over the parietal cortex were also not significantly different (100 ms: $t(7) = .812, p = .443$; 200 ms: $t(7) = 1.625, p = .148$).

A comparison between the touch-absent conditions (Light and Catch trials) was made to determine the false alarm effects of the visual stimulus when the electrotactile pulse was not present. A 2 x 2 x 3 mixed-factor ANOVA was conducted on the touch detection data with the within-subject factors of TMS site (parietal and frontal), condition (Light and Catch trials), and SOA (100 ms, 200 ms, and no TMS trials). Overall, subjects did not produce different false alarm rates between the Light trials compared to the Catch trials, and the main effect of condition was not significant ($F(1,7) = .472, p = .514$). The main effect of SOA was almost significant ($F(2,14) = 3.632, p = .054$), and the interaction between condition and SOA also approached significance ($F(2,14) = 3.690, p = .052$). When the TMS pulse was present on a trial, participants were significantly more likely to report feeling a tactile pulse compared to no TMS trials (Figure 11 A and B). However, the main effect of TMS location was not significant ($F(1,7) = .066, p = .805$). The TMS interactions with condition and SOA were also not significant ($F(1,7) = .224, p = .651$ and $F(2,14) = .448, p = .648$, respectively), and neither was the interaction between TMS, condition, and SOA ($F(2,14) = 1.021, p = .385$).

Again, individual comparisons between specific conditions were made. At the frontal TMS site, participants felt less illusory touches on the Light trials compared to the Catch trials when TMS was not delivered, but this -1.9% difference was not significant ($t(7) = -.367, p = .724$). The 3.3% false alarm difference between the Light and Catch trials when TMS was delivered 200 ms after the stimuli over the frontal cortex was also
not significantly different ($t(7) = 1.224, p = .260$), but the 4.0% increase in the Light condition when the TMS was delivered 100 ms after the stimuli over the frontal cortex was significant ($t(7) = 2.366, p = .050$). At the parietal TMS site, participants felt less illusory touches on the Light trials compared to the Catch trials when TMS was not delivered, and this -7.2% difference was marginally significant ($t(7) = -2.072, p = .077$). The 4.5% false alarm difference between the Light and Catch trials when TMS was delivered 100 ms after the stimuli over the parietal cortex was not significantly different ($t(7) = 1.066, p = .322$), but the 5.5% increase in the Light trials compared to Catch trials when the TMS was delivered 200 ms after the stimuli over the parietal cortex was almost significant ($t(7) = 2.348, p = .051$).

Reaction Time. A 2 x 2 x 4 x 3 mixed-factor ANOVA was conducted on the RT data to determine if any laterality effects occurred between the left and right hands and/or hemispheres. The four factors were the between-subject factor of tested hand/hemisphere (left and right) and the within-subject factors of TMS site (parietal and frontal), condition (Both, Touch, Light, and Catch), and SOA (100 ms, 200 ms, and no TMS trials). The main effect of hand/hemisphere was not significant ($F(1,6) = .360, p = .570$). Furthermore, none of the interactions involving the factor of hand/hemisphere were significant (all $F$'s < .996, all $p$'s > 0.4). Therefore, the factor of hand/hemisphere was collapsed across in all further analyses.

A 2 x 4 x 3 mixed-factor ANOVA was conducted on the RT data with the within-subject factors of TMS site (parietal and frontal), condition (Both, Touch, Light, and Catch), and SOA (100 ms, 200 ms, and no TMS trials). As shown in Figure 12 (A and B), reaction times across the 4 conditions were significantly different from one another
Figure 12. (A) The RT results for the frontal TMS condition in Experiment 9 are shown. (B) The RT results for the parietal TMS condition are shown.
\( F(3,21) = 6.306, p < .003 \). The main effect of SOA was also significant \( F(2,14) = 222.060, p < .001 \) and demonstrated that when the TMS pulse was fired subjects were slower to respond compared to the no TMS trials. Specifically, participants responded fastest on the no TMS trials and slowest on the trials where TMS was delivered 200 ms after the stimulus, which resulted in a significant linear trend for the SOAs \( F(1,7) = 634.247, p < .001 \). However, the interaction between condition and SOA was not significant \( F(6,42) = 1.390, p = .241 \). The main effect of TMS location was not significant \( F(1,7) = .424, p = .536 \). The TMS interactions with condition and SOA were also not significant \( F(3,21) = .839, p = .488 \) and \( F(2,14) = 1.598, p = .237 \), respectively. Finally, the interaction between TMS, condition, and SOA was not significant \( F(6,42) = .496, p = .808 \).

A comparison between the touch-present trials (Both and Touch conditions) was made to determine the effect of the visual stimulus on how quickly participants reported the electrotactile stimulus. A 2 x 2 x 3 mixed-factor ANOVA was conducted on the RT data with the within-subject factors of TMS site (parietal and frontal), condition (Both and Touch trials), and SOA (100 ms, 200 ms, and no TMS trials). Overall, subjects reported feeling the tactile pulse more quickly when a light was present on Both vision and touch trials compared to the Touch trials, which resulted in a main effect of condition \( F(1,7) = 14.744, p = .006 \). The main effect of SOA was significant \( F(2,14) = 102.933, p < .001 \), while the interaction between condition and SOA was also significant \( F(2,14) = 4.595, p = .029 \). However, the main effect of TMS location was not significant \( F(1,7) = .362, p = .566 \). The TMS interactions with condition and SOA were also not
significant ($F(1,7) = 2.101, p = .190$ and $F(2,14) = .852, p = .448$, respectively), and neither was the interaction between TMS, condition, and SOA ($F(2,14) = .679, p = .523$).

A comparison between the touch-absent conditions (Light and Catch trials) was made to determine the effects of the visual stimulus on subjects’ reaction times when the electrotactile stimulus was not present. A $2 \times 2 \times 3$ mixed-factor ANOVA was conducted on the RT data with the within-subject factors of TMS site (parietal and frontal), condition (Light and Catch trials), and SOA (100 ms, 200 ms, and no TMS trials). Overall, subjects responded faster on Light trials compared to the Catch trials, and the main effect of condition was significant ($F(1,7) = 11.001, p = .013$). The main effect of SOA was also significant ($F(2,14) = 96.079, p < .001$); however, the interaction between condition and SOA was not significant ($F(2,14) = .394, p = .682$). The main effect of TMS location was also not significant ($F(1,7) = .439, p = .529$). The TMS interactions with condition and SOA were both not significant ($F(1,7) = .737, p = .419$ and $F(2,14) = 1.015, p = .387$, respectively). Finally, the interaction between TMS, condition, and SOA was not significant ($F(2,14) = .470, p = .634$).

**Signal Detection Analyses.** A $2 \times 2 \times 3$ mixed-factor ANOVA was conducted on the $d'$ data with the within-subject factors of TMS site (parietal and frontal), condition (Both and Touch trials), and SOA (100 ms, 200 ms, and no TMS trials). The main effects of condition and SOA were not significant ($F(1,7) = 1.089, p = .331$ and $F(2,14) = 1.337, p = .294$, respectively); however, the interaction between condition and SOA was significant ($F(2,14) = 7.796, p = .005$). The main effect of TMS location was not significant ($F(1,7) = .168, p = .694$). The TMS interactions with condition and SOA were also not significant ($F(1,7) = 1.094, p = .330$ and $F(2,14) = .801, p = .468$,
respectively). Finally, the interaction between TMS, condition, and SOA was not significant \((F(2,14) = 1.702, p = .218)\). As shown in Figure 13A, the baseline values when the TMS was not delivered varied greatly between the frontal and parietal conditions, which resulted in the significant interaction. This variation in frontal and parietal baseline sensitivity values was likely due to the fact that reported detection rates on which they were based varied widely as well.

A 2 x 2 x 3 mixed-factor ANOVA was conducted on the response bias \(c\) value data with the within-subject factors of TMS site (parietal and frontal), condition (Both and Touch trials), and SOA (100 ms, 200 ms, and no TMS trials). The main effect of condition approached significance \((F(1,7) = 4.047, p = .084)\), while the main effect of SOA was significant \((F(2,14) = 5.900, p = .014)\). However, the interaction between condition and SOA was not significant \((F(2,14) = .201, p = .820)\). The main effect of TMS location was not significant \((F(1,7) = .206, p = .664)\). The TMS interactions with condition and SOA were also not significant \((F(1,7) = .089, p = .774\) and \(F(2,14) = .400, p = .678\), respectively). Finally, the interaction between TMS, condition, and SOA was not significant \((F(2,14) = 1.063, p = .372)\). As shown in Figure 13B, the criterion values were very similar between the Both and Touch conditions at each of the TMS SOAs. However, participants’ decreased their response biases in the Both vision and touch condition when the TMS was delivered 200 ms after the stimuli over the parietal cortex compared to the other conditions. While the \(c\) values between the 200 ms Both light and touch conditions were only marginally significant when comparing the difference between the frontal and parietal cortices \((t(7) = 1.579, p = .079,\) one-tailed\), the differences between both 200 ms Touch conditions (frontal and parietal) and the 200 ms
Figure 13. (A) The sensitivity results in Experiment 9 are shown. (B) The response bias results are shown.
parietal Both condition were significant ($t(7) = 2.546$, $p = .019$ and $t(7) = 3.005$, $p = .010$, one-tailed, respectively). With more subjects, it is likely that the 200 ms parietal Both vision and touch condition would show a significant reduction in participants' response biases compared to the 200 ms frontal Both condition.

Discussion

Overall, the results in Experiment 9 were different compared to the previously reported data, such as Experiments 1-5 in Johnson et al. (2006) and Experiments 6 and 7 described earlier. During the no TMS trials, the baseline detection conditions tended to vary greatly between the parietal and frontal TMS conditions, even though TMS was not actually being delivered on those trials and they should have therefore been very similar. This variance was likely due to the small sample size in Experiment 9. Nevertheless, the TMS experiment found a significant increase in tactile detection rates during Both vision and touch trials compared to Touch trials overall, but an effect of TMS location was not found. The false alarm data was similar in the no TMS baseline conditions, but subjects reported feeling more touches during the Catch trials compared to the Light trials, which has not been demonstrated in any of the previously described experiments. However, during TMS trials participants reported more touches during the Light trials compared to the Catch trials, which resulted in an almost significant interaction between condition and SOA ($p = .052$) when analyzing the false alarm data. The sensitivity data in Experiment 9 also varied widely during no TMS trials, but mimicked the detection data which found a large difference between Both and Touch trials during the no TMS parietal conditions compared to the small difference between the no TMS frontal conditions. However, the response bias data was more straightforward and clearly showed that the presence of the
TMS pulse significantly lowered subjects' response criteria, and they therefore reported more touches during TMS trials. Furthermore, TMS over the parietal cortex at 200 ms significantly lowered participants' $c$ values during both vision and touch trials compared to the other conditions. This response bias correlated with a non-significant increase in reported touch detection when TMS was delivered at 200 ms over the parietal cortex.

With more participants, it is possible that this visual enhancement effect could be significant during both light and touch trials with TMS at 200 ms over the parietal cortex. As shown in Figure 12 (A and B), the RT data in Experiment 9 increased linearly resulting in greater RTs for longer TMS SOAs, but did not differ between the frontal and parietal conditions. Also, subjects responded faster during both vision and touch trials compared to Touch trials overall.
General Discussion

The purpose of this set of experiments was to determine the location and temporal sequences associated with the visuotactile interactions described in Johnson et al. (2006). The study found that a non-predictive visual stimulus simultaneously presented with an electrotactile stimulus significantly increased subjects’ reported touch detection. In Experiments 1-5, a small red LED served as the visual stimulus, while the tactile stimulus was a small electrical pulse delivered to a participant’s finger. Johnson and colleagues also discovered that subjects felt more illusory touches during trials where the visual stimulus was presented without the tactile pulse. Compared with the reported increase in detection, the false alarm increase was relatively small overall and non-significant in Experiments 1 and 3. However, when the data was analyzed using signal detection analyses, the tactile enhancement found during trials when the visual stimulus was present was due to a response bias. Subjects were therefore shifting their criteria for detecting touch lower during light-present trials compared to light-absent trials. Johnson et al. also found a small effect of sensitivity across Experiments 1-3 and subjects’ touch perception was slightly greater when a light was simultaneously presented with a tactile pulse. In the Johnson et al. experiments, participants were responding to both the electrotactile and visual stimuli; whereas in the current experiments, subjects were only required to respond whether or not they had felt the tactile pulse on each trial. The reason for this change was to determine if vision would still influence tactile perception if the light became irrelevant and participants did not have to pay attention to or respond to the visual stimulus.
In the current set of experiments, Experiment 6 was a replication of Experiment 1 and had four conditions: Both, Touch, Light, and Catch trials. However, participants were only required to respond whether or not they had felt the tactile pulse, but were asked to look at their hand so as to see the visual stimulus if it flashed. The experiment demonstrated that when a concomitant light was presented with touch, subjects reported feeling the tactile pulse more often. Although this enhancement was significant, it was not as pronounced as in previously described experiments, most likely because the light was irrelevant in this experiment and therefore had less of an influence on participants' responses. However, what is interesting is that the visual stimulus still increased the perception of touch in subjects, in both touch-present and touch-absent trials. However, it was not an increase in sensitivity driving the tactile enhancement, but a response bias to report additional touches during light-present trials. The criterion shift was also evident in the false alarm difference, which was nearly identical to the detection difference (4.7% vs. 5.3%, respectively). The similar increases in detection and false alarm percentages demonstrated how processing of an irrelevant, non-informative, simultaneous visual stimulus can still influence subjects' reported feelings of touch. This effect could be due to a learned cognitive association between vision and touch because humans tend to rely heavily on visual information.

Experiment 7 was designed to determine the temporal sequence of processing visual and tactile interactions described previously in Johnson et al. (2006) and Experiment 6. This experiment had various SOAs ranging from -100 ms to +100 ms with 25 ms increments between the visual and tactile stimuli. Detection results demonstrated that at shorter SOAs, subjects reported significantly more tactile pulses
during Both vision and touch trials compared to Touch trials. At longer SOAs, however, the enhancement is still greater than the tactile baseline, even though the Both light and touch trials are not significantly different from the Touch trials. As shown in Figure 6, the Both vision and touch trials with shorter SOAs had larger percent increases in reported touch compared to the Both trials with longer SOAs, which resulted in a significant quadratic trend. The smaller the asynchrony between the visual and tactile stimuli, the greater the enhancement in touch detection. This result makes sense empirically because a real visuotactile event happens simultaneously. Therefore, the visual stimulus should have a greater effect on tactile processing the closer in time that they occur. The data in Experiment 7 demonstrated that at asynchronies of ± 100 ms, the visual stimulus had less of an influence on tactile processing than at shorter SOAs. At asynchronies greater than 100 ms, it is likely that the light will have even less influence on touch.

When the signal detection results were analyzed, however, a change in sensitivity was not found for the Both light and touch trials compared to the Touch trials, even though the $d'$ values varied quadratically so that shorter SOAs had greater $d'$ values. As shown in Figure 8A, at short SOAs, subjects' sensitivity was not significantly different from the Touch trials, even though the values were greater. These results mimic those in Experiment 1-3, which found a small effect of sensitivity across experiments even though the differences were not significant within experiments (Johnson et al., 2006). The increase in touch detection during Both visual and tactile trials was therefore due to a response bias where subjects lowered their criteria for reporting touch with a nearly simultaneously presented light stimulus. Participants Both $c$ values were significantly
less than their Touch $c$ values at all SOAs. This large response bias to report feeling a
touch with a concomitant light also extends to visual stimuli presented up to 100 ms
before and 100 ms after the presentation of the tactile pulse. The significant quadratic
trend shown in Figure 8B demonstrated that as the SOA between the visual and tactile
stimuli increased, the less influence the light had on subjects' reported feelings of touch.
Therefore, at SOAs greater than 100 ms, it is likely that the criterion values between Both
vision and touch trials and Touch trials will not be significantly different.

Experiment 8 demonstrated that participants found it very difficult to decide
whether a visual stimulus or an electrotactile stimulus had been delivered first. The
experiment had 8 SOAs varying from -100 ms to +100 ms with 25 ms increments
between vision and touch. As participants were forced to choose which modality arrived
first, light and touch were not presented simultaneously. In this experiment, negative
SOAs refer to the visual stimulus arriving prior to the tactile pulse; whereas, positive
SOAs refer to the touch arriving before the light. During trials where the electrotactile
stimulus was delivered first, subjects could not determine which modality had arrived
first and their detection percentages did not differ from chance. These results are
somewhat problematic given research that showed that participants could distinguish
which modality arrived first at similar SOAs as those in Experiment 8 (Spence et al.,
2001; Spence et al., 2003). However, the previous research used vibrotactile stimulators
(Spence et al., 2001; Spence et al., 2003), which are considerably easier for subjects to
feel compared to the electrical stimulation used in this experiment. Spence and
colleagues (2003) also demonstrated that when the spatial information between the two
modalities (vision and touch) was the same, participants found it more difficult to
distinguish which sensory modality had arrived first. In Experiment 8, the visual stimulus was taped directly over the ring electrodes which were delivering the tactile pulse; thus both modalities were providing the same spatial information to the brain. This is one possibility why when the electrotactile stimulus preceded the visual stimulus, participants were no better than chance at detecting which modality (touch) had arrived first, even at an asynchrony of 100 ms. Experiment 8 demonstrated that when the spatial information between the two modalities is identical and the tactile stimulus is difficult to detect, then it was much more difficult for participants to decide *when* the touch had occurred in this experiment compared to *if* the touch had occurred in previous experiments.

Experiment 9 was designed to determine the cortical location and temporal sequence associated with visuotactile processing. In the experiment, TMS was delivered over the frontal and parietal cortices at two different TMS SOAs (100 & 200 ms) after visual and/or tactile presentation. We had hypothesized that magnetic stimulation over the posterior parietal cortex would disrupt normal processing of crossmodal interactions between vision and touch, which would result in a decrease in the reported feelings of touch during light-present trials. However, the detection results did not significantly vary between the frontal and parietal cortices in Experiment 9. Instead, this experiment demonstrated that when TMS was delivered over the posterior parietal cortex 200 ms after the visual and tactile stimuli had been delivered, participants significantly lowered their response criteria for reporting electrotactile stimulation (Figure 12B). This response bias actually resulted in an increase in touch detection during both vision and touch trials with TMS delivered 200 ms over the posterior parietal cortex (Figure 11B). However,
the 7.5% detection increase in both light and touch trials compared to touch trials at 200 ms was not significant, even though the difference was significant during the no TMS trials. Interestingly, the 5.5% increase in false alarms during the Light trials compared to the Catch trials at 200 ms was significantly different. Therefore, TMS delivered over posterior parietal cortex 200 ms after visual and tactile stimulation appeared to enhance the previously described response bias to report touch with a concomitant light. However, it is difficult to determine if the increase in reported touch during light-present trials after TMS over the parietal cortex at 200 ms is a legitimate or spurious result, given the small sample size in Experiment 9, the baseline detection differences between the no TMS trials over the frontal and parietal cortices, and the overall increase in touch detection after magnetic stimulation.

Unlike Experiments 1-5 (Johnson et al., 2006), Experiments 6-9 recorded participants’ reaction times in an attempt to understand some of the temporal processes associated with visuotactile interactions. Experiment 6 demonstrated that subjects responded fastest on both trials where visual and tactile stimuli arrived simultaneously and slowest on Catch trials where no sensory stimulation was delivered. One might assume this effect was due to the fact that subjects were responding “yes” much faster on the light-present both trials and “no” much slower on the light-absent Catch trials. However, this was not the case because the Light and Touch trials had similar average RTs even though participants were responding “yes” approximately 40% more often on the Touch trials compared to Light trials. The detection and RT data in Experiment 6 demonstrated that the presence of a visual stimulus significantly influenced tactile processing so that touches were reported faster and more often on light-present trials.
Experiment 7 had similar RT results as Experiment 6 and subjects responded faster on trials where a light was presented. More specifically, the earlier the light was presented on a Both light and touch trial, the faster the subjects responded. This significant linear trend for Both vision and touch trials indicated that participants were waiting for the light to be delivered before they responded whether or not they had felt a touch, even though the visual stimulus was irrelevant. In addition, Both light and touch trials where the visual stimulus was delivered 50 ms or more before the electrotactile stimulus were significantly faster than the Light, Touch, and Catch trials. In Experiment 8, subjects displayed unusually long response times and did not demonstrate a significant RT difference between conditions. It is likely that subjects were waiting for both stimuli to be delivered before determining which modality had arrived first. In addition, participants found the TOJ task very difficult, which could have contributed to the delayed RTs. In Experiment 9, subjects were faster at responding overall when magnetic stimulation had not been delivered. This effect resulted in a significant linear trend and participants responded the slowest on trials with the 200 ms TMS SOA. The RT results were very similar between the frontal and parietal cortices in Experiment 9, indicating that magnetic stimulation interfered with subject’s response times overall. Similar to the previous experiments, participants responded faster on Both light and touch trials compared to the other trials. But this effect was much less pronounced compared to Experiments 6 and 7.

Across all the experiments, the RT data did not provide a great deal of insight into the temporal aspects of subjects’ visuotactile processing. The one effect that was demonstrated across experiments was that participants were specifically faster on Both
vision and touch trials and usually faster on light-present trials, even though the visual stimulus was irrelevant and did not require a response. It is possible that when the visual stimulus was present, subjects were more likely to feel a touch due to a response bias and were also more certain of the suprathreshold light and thus responded faster. Overall, the RT data showed similar results as the signal detection analyses in that the presence of a visual stimulus altered participants' criteria for responding to touch.

This study investigated how a simultaneous, non-informative, and irrelevant visual stimulus influenced tactile processing. Johnson and colleagues (2006) previously demonstrated that participants were more likely to report feeling a touch when a concomitant light was presented, regardless of whether the tactile pulse had actually been given on a trial. The resulting increase in detecting real and illusory touches during light-present trials was due to a significant response bias to report electrotactile stimulation with simultaneous visual presentation. The current set of experiments not only replicated these basic findings, but also investigated the temporal processes associated with the visuotactile interactions. The experiments demonstrated participants responded more quickly on light-present trials compared to light-absent trials, especially when both the visual and tactile stimuli were delivered simultaneously. The experiments showed that even though subjects were not required to respond to the visual stimulus, it still influenced participants’ reported feelings of touch. Experiment 7 determined that vision has a larger influence on tactile processing the smaller the temporal asynchrony between the visual and tactile stimuli. This result makes sense empirically because real crossmodal events happen simultaneously. Experiment 9 sought to determine the temporal sequence of visuotactile processing and where the crossmodal enhancement
occurred in the brain. While the TMS experiment did not resolve the exact location of
the enhancement in the brain, it did demonstrate that significant crossmodal processing
occurred in the posterior parietal cortex 200 ms after the stimulus presentation. Further
research using a focal figure-eight TMS coil with more cortical stimulation sites over the
parietal cortex and additional magnetic stimulation asynchronies needs to be conducted to
determine the exact location and temporal sequencing of the visuotactile crossmodal
processing found in these experiments. Determining the location and temporal aspects
involved with these visuotactile interactions could have broad implications regarding
neural processing involved with vision and touch that could lead to better rehabilitative
measures for patients with visual and/or tactile deficits.
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layout of hand, eye, calculation, and language-related areas in the human parietal


